Optimisation of intake trashracks

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Introduction

In design of hydropower plants in Iceland the size of intake trashracks has predominantly been based on approach gross velocity of about 1,0 m/s. This assumption has prevailed throughout the years and goes back to the 1960s when large hydropower development was initiated by Landsvirkjun (The National Power Company of Iceland) with the construction of Búrfell HEP, a 210 MW hydropower plant located in Þjórsá River in South Iceland. Landsvirkjun and has been at the forefront of the nation's hydropower development. Since Búrfell HEP was commissioned in 1972 Landsvirkjun has commissioned five other large hydropower plants in the Þjórsá River in addition to two other large projects; Blanda HEP a 150 MW station in North Iceland and the 690 MW Kárahnjúkar HEP in the East. The environmental conditions are essentially similar for all the projects, the harnessed water comes from glacial rivers where the catchment area and reservoirs are located in rural uninhabited areas with no forest and little vegetation. As a result little to none trash or debris reaches the intake structures. There is however considerable frazil and anchor ice problems in most of the stations due to shallow intakes and cold but unstable weather. This results in problems with ice clogging the trashracks. In the worst places the top trashrack panels are lifted and kept on dry land throughout the winter and re-installed in the spring.

Landsvirkjun is now preparing four other large hydro projects on the Þjórsá River with the 100 MW Búrfell Extension HEP first in line. This includes a single Francis turbine unit with design discharge close to 100 m^3/s and H_n=120 m. Since the size of the trashracks considerably affect the intake size and cost it was decided to conduct a feasibility study of an intake of similar dimensions as the proposed Búrfell Extension HEP with various approach velocities, ranging from 1,0-3,0 m/s with 0,25 m/s interval. It was further decided to analyse the effect of other main design parameters that are generally considered in trashrack design such as differential design pressure due to clogging, spacing of rack bars, head losses and risk of vibration in the steel profiles.

The study executed for Landsvirkjun also included gathering the design assumptions and main dimensions for all the existing large hydroelectric intake trashracks, together with the experience with operation and maintenance. Further, an extensive research was conducted in international literature and published papers on trashrack design. This paper addresses the optimisation but for other topics reference is made to (1).

Spreadsheet models were prepared for the design and calculations of the concrete volumes and the weight of the trashrack steel structure, with various assumptions. This enabled effective output of the main cost factors when the design parameters were altered. In total some 20 different intake structures were analysed and up to 60 cases of variable types of the steel trashracks analysed. Head losses were estimated and a total cost curve drawn up to highlight the optimal design approach velocity for the pertinent intake and trashrack structures. The design models were structured so they could be used generally with various design, capacity and size assumptions.

1. Model for dimensions of concrete structure

1.1 General

An Excel model was created in order to calculate the concrete volume of various types of intake sizes for a single penstock intake, based on the design discharge together with different approach velocity, submergence and other main assumptions, with and without a middle pillar. The main concrete volumes were calculated but other parts of the structures that were not affected by the various trashrack sizes were excluded. These mainly include wing walls, intake control building and concrete downstream of the intake back wall, i.e. around the square to circular transition piece. Other cost items such as excavation, grouting works, metalwork and other finishes were also excluded.

The construction cost was obtained by assuming a fixed unite price for the concrete volume, including the average cost of formwork and reinforcement and all other indirect construction cost (20% in addition).

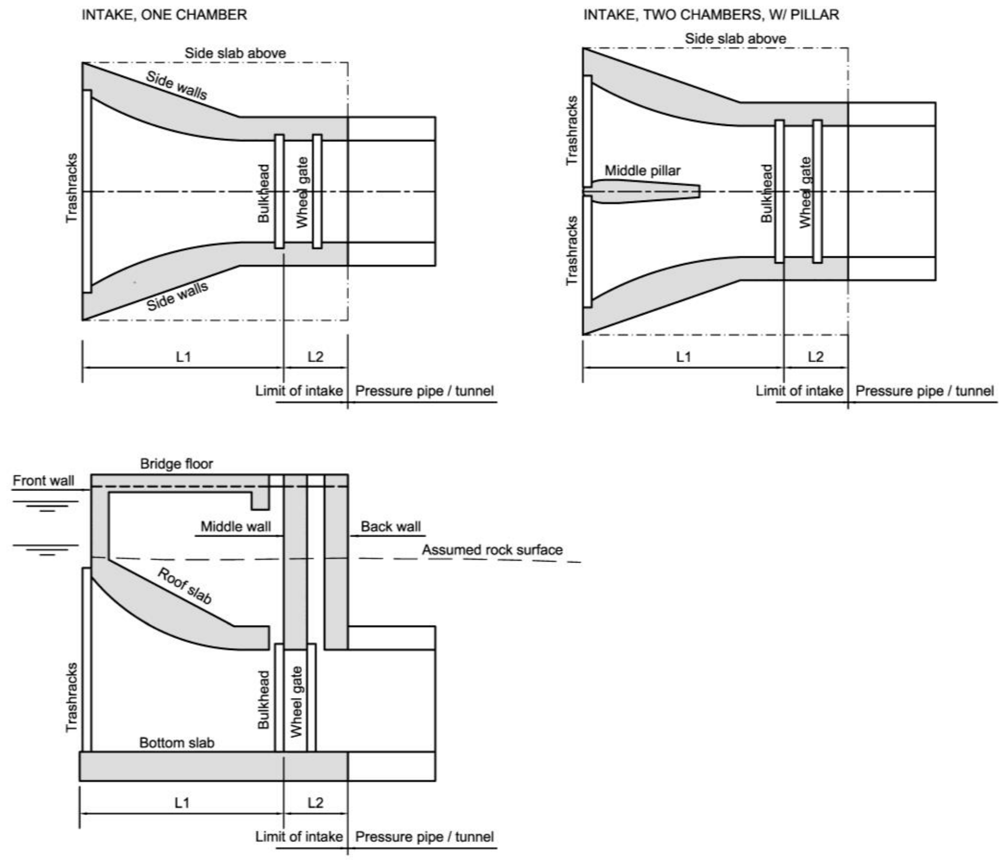

Figure 1. The intake model structure showing the main dimensional parameters (drafted from Gordon (2)).

1.2 Model parameters

Some of the input parameters in the model were fixed in this study during the execution of the 2 x 9 different cases evaluated. These include i.a. the design discharge, size of the gates (for simplification the bulkhead service gate and main gate had the same dimensions), upstream water levels, the proportional decrease of the water velocity between the trashracks and the gates and assumed depth to sound rock. The wall and slab thicknesses were estimated by a ratio against the water pressure and the span of intake chamber(s). The main variable input parameters in this particular study included the approach velocity and the width and height of the trashracks. It was assumed that the w x h ratio of the trashracks would be within 1,5-2,0.

1.3 Results

The most important parameter of the intake regarding increased mass due to larger trashracks is the distance L1, from the gates to the trashracks (see Figure 1). This is because the side walls are very high and each m length is very costly in comparison with the slabs and other walls. It took considerable research to find some literature on how to estimate the distance L1 and thus how steep the transformation is allowed to be. The only reference found was from *Murray and Gordon* (3) who recommend that the transformation does not exceed 0,5 (m/s)/m. The distance in the model was however based on experience from some existing intakes in Iceland where the transformation ratio ($\sqrt{A_{trashracks}} - \sqrt{A_{main\ gate}}$)/ L1) varied somewhat but an average value of 0,40 ended up being used, which did not significantly violate the Murray and Gordon criteria.

In this study the intake was concreted against bedrock as the harnessed water will be conveyed though a short horizontal tunnel, to a vertical penstock and an underground powerstation. Thus, the stability of the structure was not part of the scope of work but this needs to be checked in each case to satisfy the necessary requirements. In the cases where stability requirements call for longer intake (L1), than the criteria used here, the installation of larger trashracks would require less extra concrete with the optimisation yielding larger optimum trashracks area compared to what is presented here.

2. Trashracks

2.1 Design model

An Excel model was prepared for the steel trashrack design. It is structured for preliminary design of trashracks in order to evaluate the steel weight so that a cost estimate can be established for various sizes and configuration of the trashracks.
The model is rather extensive and includes i.a. the following input parameters; size of trashrack opening (based on the approach velocity), width and height, number of panels, steel quality and pertinent yield strength, differential design pressure, width and depth of rack bars, factor of safety regarding forcing frequency against natural frequency, degrees of end fixity, etc. This gives the structural limits of various steel profiles which are adjusted in each case; the vibration factor of the rack bars, the appropriate stresses, buckling of vertical centre beams, etc. The end output of the model includes the total weight of the trashrack steel but excluded are the embedded guides and their fastenings. These are estimated by a cost model (Kolla 7.0) that has been developed by Landsvirkjun throughout the years and is updated yearly.
The study undertaken was in part twofold; a) a double chamber trashrack and b) a single chamber trashrack. The main assumptions include: The rack bars were set 15 x 75 mm (1:5 ratio) with c/c 150 mm, allowable bending stresses 45% of the material yield strength, differential design pressure 9 m, factor of safety regarding vibration S_f=3 and end fixity α=16 (K=2,55). These assumptions were the same for all these 18 cases, i.e. nine cases for the single chamber layout and nine for the double chamber configuration. It was further decided that each panel should not weigh more than 6000 kg.

2.2 Results of trashracks model analysis

The results showed that the total steel weight is in all cases considerably higher for a double chamber trashracks than the single one for the same approach velocity and thus the same total area, even so for the largest 100 m^2 opening area. This is mainly because the structural side beams of the trashracks weigh considerably in the total weight of the steel structure. Thus, significant cost reduction can be achieved by implementing one chamber instead of two as the side beams and the embedded guides are cut by half. Longer structural spans in one chamber appear to have less effect.
The investigation further indicated that the cost of the steel trashracks increased by 33% by increasing the differential design pressure from 3 m to 21 m. The safety factor against vibration and the rack bar size had on the other hand no significant effect on the construction cost of the trashracks, although the latter had some effect on the head losses. The same applies to the distance between the rack bars, but significant cost increase was because of higher head losses as shown in Figure 4.

3. Head loss assumptions and related cost

Head loss (ΔH) through the trashracks was calculated with the formula proposed by Meusburger (4):

$\Delta H = K_t * V^2/(2g)$ where $K_t = 2{,}42*(P/(1-P))^{1,5}$

Where;
V is the gross velocity through the trashracks (V=Q/A) in m/s and P is the blockage ratio, i.e. the total area perpendicular to the flow blocked by the racks and the structural steel profiles, compared to the total area (A).

The yearly cost associated with decreased energy generation due to head loss through the trashracks every year through the amortisation time of the project must be calculated and the present value evaluated to compare the cost of lost energy generation to the construction cost. This was calculated through the following formulas:

$C = \Delta E \cdot JE * 10^{-6}$ = Total present value of future annual cost due to head loss (MISK[1]).

Where;

$\Delta E = \gamma * \Delta H * Q_{max} * \eta * 8760 * \beta$ = energy lost due to head loss per year (Wh/a).

JE = IE * P = Present value of yearly energy produced yearly in the future, ISK/(kWh/a).

IE = Reference value of energy, ISK/kWh (4,95 ISK/kWh or 43 USD/MWh used in this study).

[1] ISK is the Icelandic national currency; MISK=ISK*10^6, USD=115 ISK (2014 values).

P = Present worth factor due to equal annual income. Here used 17,3, based on 4% interest rate and 30 years amortisation).

γ = unit weight of water, 9810 (N/m^3).

ΔE = Head loss through trashracks for full discharge, Q_{max} (m).

Q_{max} = Reference discharge. Usually maximum discharge (m^3/s), here 100 m^3/s.

η = Utilisation of turbine and generator (estimated 0,91).

8760 = hours in one almanac year (h).

β = Coefficient pending duration of flow through the intake (~0,2<β <1,0 for Búrfell Extension 0,9).

The coefficient β is a very convenient coefficient to use in calculations like this. It is the average unit flow through the trashracks to the third power.

$$\beta = \frac{1}{T}\int_0^T (Q(t)/Q_{\max})^3\, dt$$

Where Q(t) is the discharge at each time and T is the time period the third power average is evaluated through. The β coefficient is always between 0 and 1 and always less than the utilisation of the station (Q_{ave}/ Q_{max}).

The Icelandic hydropower plants have unusually high utilisation factor due to the fact that the electricity market is 100% served by hydropower or geothermal, the average β coefficient is probably close to 0,6. The β coefficient is therefore much higher than where the hydropower plants are used for peaking power as in most countries where 0,1 to 0,3 are common values. The expected β coefficient for the Búrfell Extension HEP considered here is 0,9 as it is an extension with better efficiency than the existing station and will therefore predominantly be utilised at full capacity.

The energy value in the small isolated electricity marked in Iceland is on the other hand much lower than in most other countries. The energy value and β coefficient are multiplied together in the cost equation above so high β coefficient and low energy price balance each other out so the cost values used here might also apply for many other countries with much higher energy values but with lower β coefficient.

4. Optimisation of total cost

Based on the aforementioned methods and assumptions the construction cost for the intake concrete and the steel trashracks are shown on Figure 2 with red and blue falling lines for different gross water approach velocity. The cost due to head loss through the trashrack is shown in green rising line and the sum of this, the total cost, is shown in brown U shaped line. The lowest total cost is thus obtained for water velocity in the range of 1,75 to 2,5 m/s. There is however small increase from 1,5 to 1,75 m/s so conservative design value could even be 1,5 m/s. In comparison the blue dotted line shows the total cost for a double chamber trashrack showing the total cost 40 to 50 MISK[2] higher as mentioned earlier with the optimum velocity being 2,0 to 2,75 m/s. It can also been seen that 90 MISK will be saved in total cost by using to the optimum velocity 1,75 m/s instead of the traditional 1,0 m/s leading to approx. 100 MISK in construction cost savings.

It is also noticeable from the figure that the main cost here is related to the concrete structure rather than the trashrack itself. The concrete differential cost weights about 5 to 10 times more than this of the trashracks.

[2] ISK is the Icelandic national currency; MISK=ISK*10^6, USD=115 ISK (2014 values).

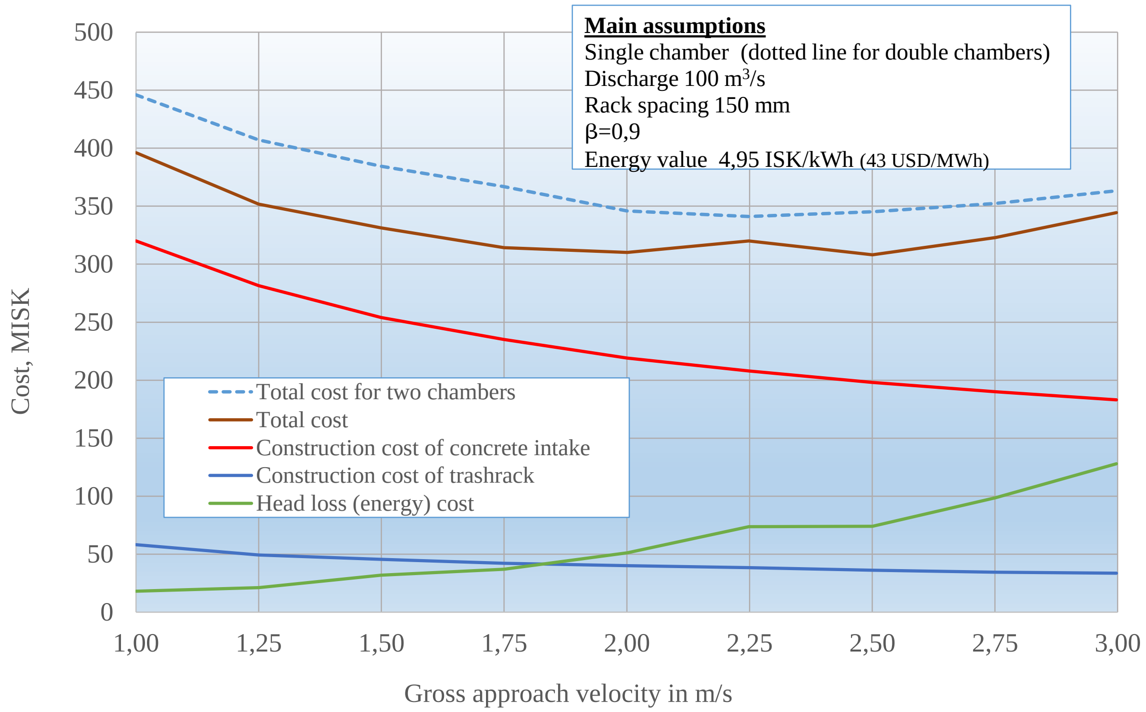

Figure 2. Results of optimisation of trashracks approach velocity.

Figure 3 shows the same results for the construction costs and the cost of head losses as in Figure 2 indicates but additionally the total cost of different energy values for sensitivity analysis. The brown line shows the energy value used in the study, 4,95 ISK/kWh, the red dotted line shows double the normal price, 10 ISK/kWh, and the blue dotted line shows the half of the energy value 2,5 ISK/kWh. Even with twice as high energy value it is feasible to use 1,75 m/s approach velocity, whereas with half the energy value (or half of the β coefficient) the optimum velocity increases to 2,5 to 2,75 m/s.

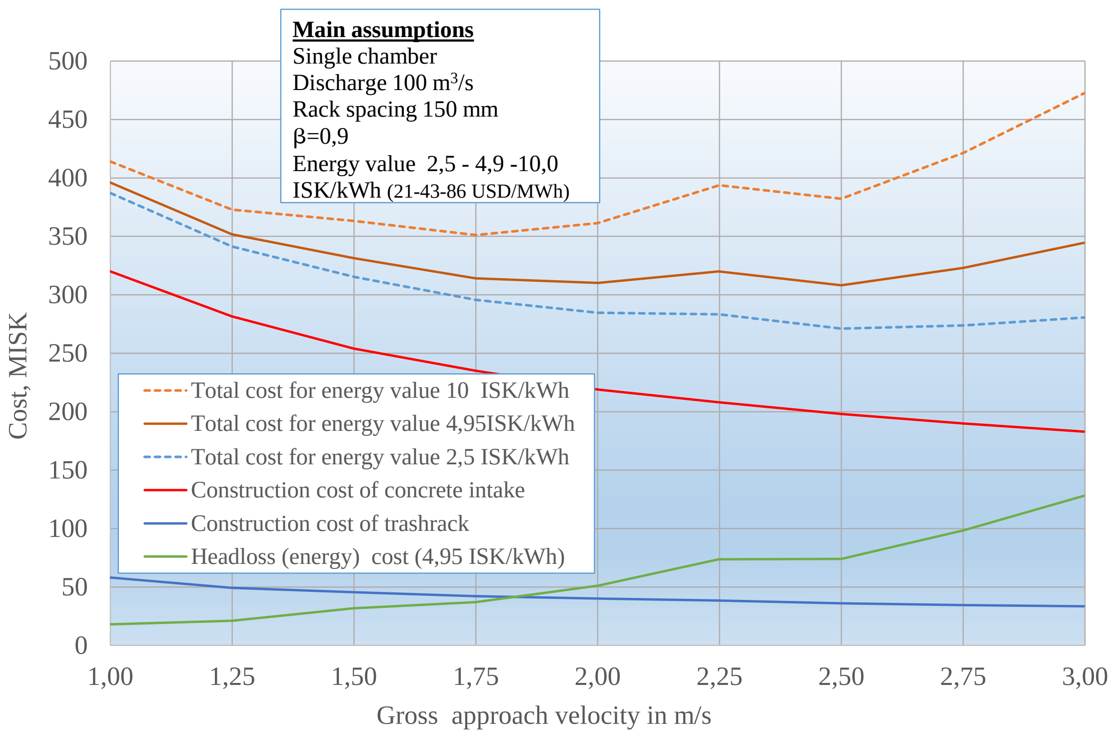

Figure 3. Results of optimisation of trashracks approach velocity with different energy values.

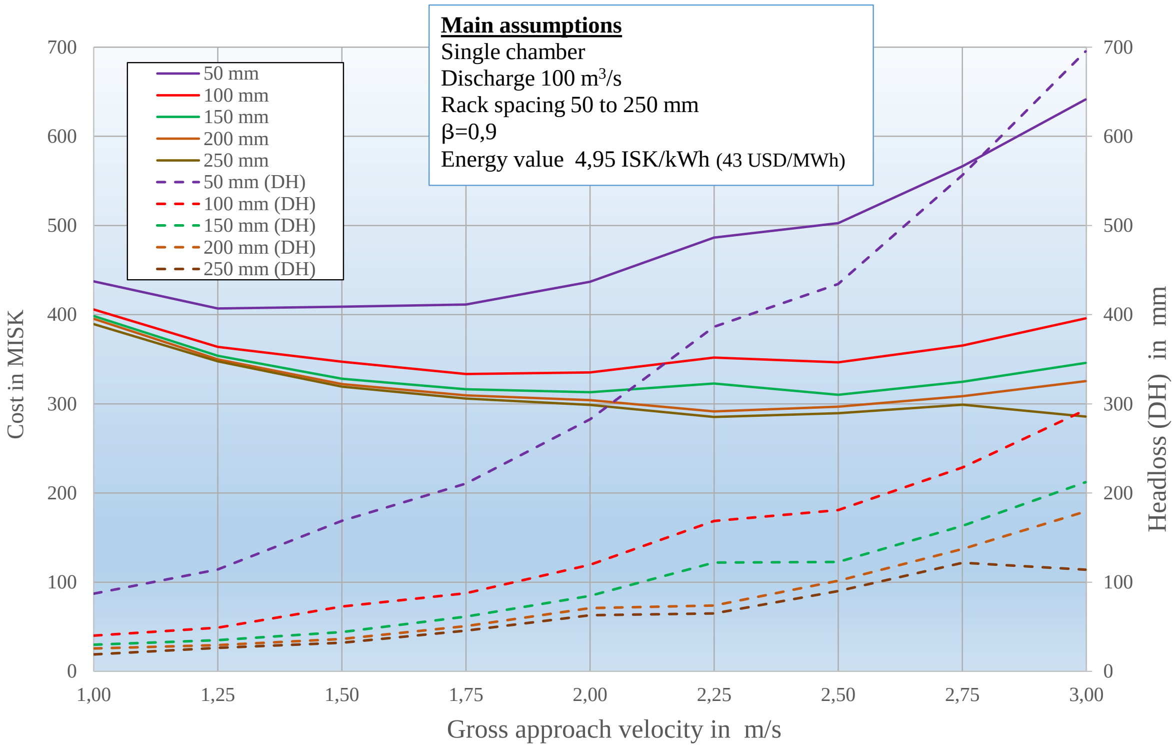

Figure 4. Results of optimisation of trashracks approach velocity for different rack spacing

Figure 4 shows the same results with c/c 150 mm between the rack bars as brown line as before, and in addition results for trashracks with spacing from 50 mm to 250 mm. All other assumptions are the same. There is no significant difference between optimum velocities for spacing between 150 mm or 250 mm. If the spacing is decreased to 50 mm the head loss increases significantly and the optimum velocity then becomes a bit lower or 1,25 to 1,75 m/s. The blockage ratio is about 0,2 for the coarsest spaced trashracks, 0,3 for the 100 mm spacing and more than 0,4 for the 50 mm spacing resulting in loss coefficient (K_t) increasing from 0,3 to 0,7 and up to 1,4 for the 50 mm spacing.

5. Results and discussion

The study shows that when considering only the total cost of installing and operating trashracks with coarsely spaced rack bars (>100 mm) for 100 m^3/s discharge in a single chamber, the optimal approach velocity proved to be higher than 1,75 m/s even considering highly utilised trashracks and high energy value. This is almost double the conventional 1,0 m/s design criteria that has generally been utilised in design of Landsvirkjun's large hydroelectric stations intake. This means reducing the opening size of the trashracks to less than 60% of the previous applied size.

Other criteria might affect the size of the trashracks, like fish and especially juvenile salmon passage, ice problems, possibility of increased capacity and general operation and maintenance has to be considered. It is nevertheless not obvious that these matters generally become significantly worse although the approach velocity is increased. Still, this has to be investigated in each case. A similar study for both a higher and a lower design discharge would be interesting in order to allow to preparation of new general guidelines regarding design velocity for large intake trashracks.

References

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