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Experimental Study of Stage-Discharge Relationships for Flows over Radial Gates and Flap Gates

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ABSTRACT: Floods forecasting and management of large regulated rivers require the ability to properly combine classical flow routing with the regulation dams that act as internal boundaries. Therefore a good knowledge of the stage-discharge relationships of these dams is mandatory. The Meuse River in Belgium is such a regulated river, for which the HYDROAXE software was developed jointly by the Belgian Ministry of Public Works (SPW-SETHY) and the Hydraulics Laboratory of the Université catholique de Louvain (Belgium). Working for a constant improvement of this software, this paper presents an experimental study of flow over a typical dam of the River Meuse, i.e. a dam controlled by radial gates equipped with flap gates. Measurements of the upstream water level and of the discharge are presented for different positions of the flap gate. According to earlier works on gates featuring a variable inclination, mainly drum gates, it is observed that the stage-discharge relationship depends on the inclination of the flap. However, the theoretical discharge coefficient obtained by means of formulae of the literature always exceeds the measured discharge coefficient. This suggests that further work is required to obtain a stage-discharge relationship adapted to the particular case of radial gates equipped with flap gates.

Keywords: Dam discharge modelling, Flood forecasting software, Physical model of gate, flow over gate, flow below gate

1 INTRODUCTION

The Meuse River in Belgium (Figure 4) is regulated through 15 dams (e.g. the La Plante dam illustrated in Figure 5) consisting of radial gates and flap gates (Figure 6). For low discharges water flows over the flap gate. This mobile part being progressively lowered when the discharge increases in order to maintain the prescribed water level in the regulated reaches. For higher discharges, the radial gate is raised incrementally and the water flows both over and under the gate. For further increasing discharges, the gates are completely raised and the water level is unregulated.

To predict the water levels along the Meuse River, the HYDROAXE software was developed at the Université catholique de Louvain, Belgium (e.g. Scherer and al. 1998, Dal Cin and al. 2005). HYDROAXE is a real-time flood forecasting tool based on the numerical resolution of the 1D Saint-Venant equations, including the Exchange Discharge Model (Bousmar and Zech 1999) to account for momentum exchanges between the minor bed and the floodplains. In its current state, HYDROAXE covers the Meuse River from the dam of Hastière close to the French border until the dam of Monsin close to the city of Liege. Based on 18-hours discharge prediction, the model provides in a few seconds the hourly evolution of the water level along this reach of about 150 km. The considered reach is equipped with 15 dams as indicated in Figure 4. The model takes into account the operation of the dam gates and their influence on the flow. In this context, the accuracy of the stage-discharge relationships used in the numerical model for the gates is crucial.

In this paper, we present an experimental study of flow over a scale model of the radial and flap gate of the La Plante dam (Figure 5). Among the wide range of stage-discharge relationships that can be found in literature for flows over weirs and gates, the formulae by Bradley (1954) and Sinniger and Hager (1989) appeared as the most appropriated for our case. These formulae are used to predict the discharge in our experiments, and the results are compared to the measurements. Finally, conclusions are drawn regarding their applicability to the Meuse River dams.

2 FLOW OVER THE GATE

2.1 *Some existing theoretical models and experimental studies concerning flows over weirs*

Among the theoretical and experimental studies about flows over weirs that can be found in the literature, only very few consider a variable flap angle (Bradley 1954, Sinniger and Hager 1989). Other models developed for sharp crested weirs may also be considered, such as those developed by Chow (1959), Naudasher (1991) or Novak (1996).

In the models proposed by Chow (1959) and by Naudascher (1991), the discharge coefficient is calculated from the known discharge and a water depth h, defined as the difference between the elevations of the water surface upstream the gate and the highest point of the gate (Figure 8). For a gate of width L, the equation proposed by Chow (1959) is

$$Q = C\,L\,h^{3/2} \tag{1a}$$

$$\text{with } C = \sqrt{0.3048}\left(3.27 + 0.40\frac{h}{w}\right) \tag{1b}$$

where the discharge coefficient C is given in ($m^{1/2}s^{-1}$). Naudascher (1991) proposed

$$Q = \frac{2}{3}\mu\sqrt{2g}L\,h^{3/2} \tag{2a}$$

$$\text{with } \mu = 0.61 + 0.08\frac{h}{w} \tag{2b}$$

In these two models, the discharge coefficient depends linearly on the value of h / w, where w is the distance between the toe and the highest point of the gate (Figure 8). It must be noted that only the upstream water level is taken into account in h, and not the total head. In the model by Novak (1996), the discharge coefficient also depends linearly on the value h / w but the total head above the highest point of the gate, denoted by H (Figure 1), is used, instead of h, to calculate the discharge:

$$Q = \mu\sqrt{2g}\,L\,H^{3/2} \tag{3a}$$

$$\text{with } \mu = 0.602 + 0.075\frac{h}{w} \tag{3b}$$

2.2 *The theoretical model based on Bradley (1954) and Sinniger & Hager (1989)*

The theoretical model is based on the work of Bradley for flows over drum gates for which the upstream face is quite similar to a flap gate. Bradley proposed the following relationship between the discharge and the total head.

$$Q = C\,L\,H^{3/2} \tag{4}$$

Where C is the discharge coefficient and L is the width of the channel.

The evolution of C [$ft^{1/2}.s^{-1}$] as a function of the angle θ between the horizontal and the tangent to the downstream lip of the gate is shown in Figure 1 following Bradley (1954), for different values of the ratio H / r, r being the radius of the gate. It must be noted that if θ is positive, the highest point of the gate is the lip of the gate; otherwise, it is the crest of the gate.

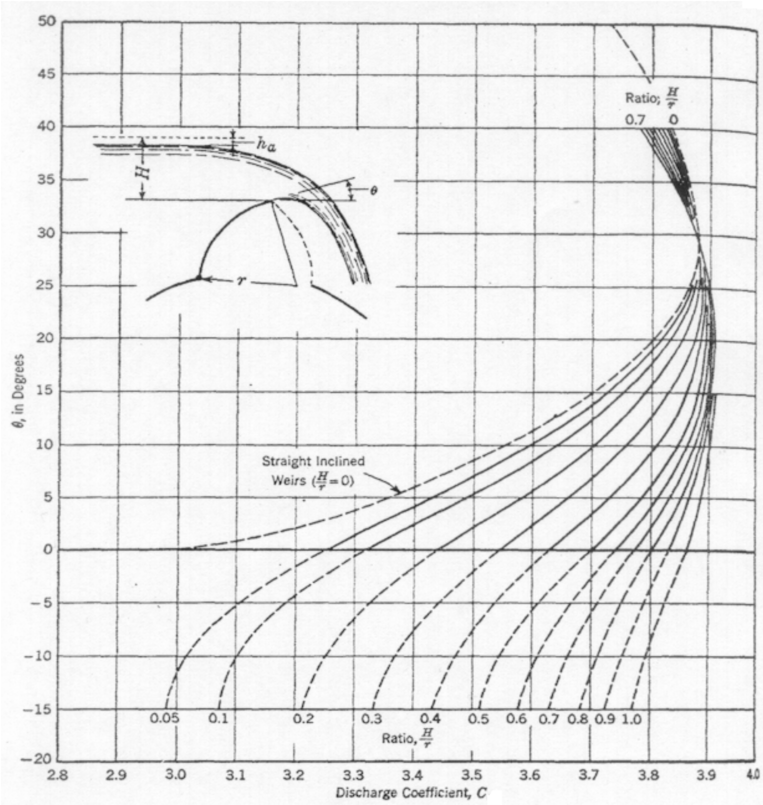

Figure 1. Discharge coefficient C [$ft^{1/2}.s^{-1}$] (Bradley 1954)

Sinniger and Hager (1989) proposed an analytical expression for the curves observed by Bradley (1954) where the discharge coefficient C is a function of θ, H/r and g, the gravity acceleration.

$$C = \sqrt{2g}\,\mu\left(\theta, \frac{H}{r}\right) \tag{5}$$

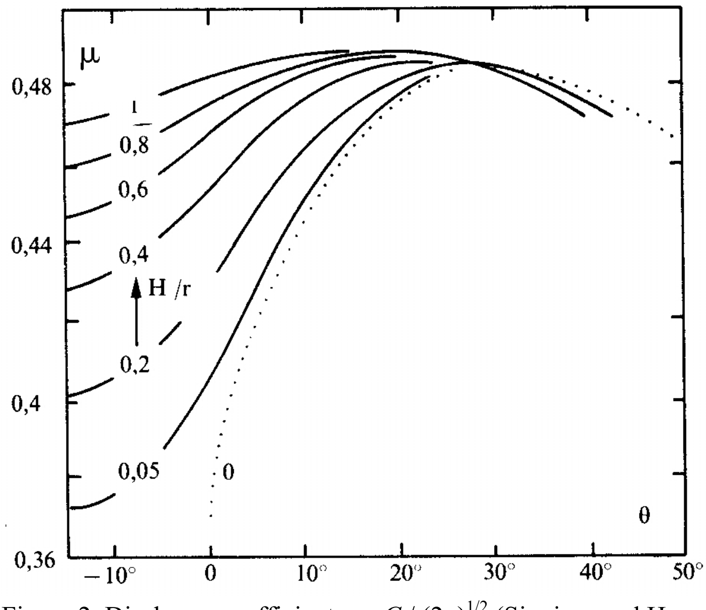

Figure 2. Discharge coefficient $\mu = C / (2g)^{1/2}$ (Sinniger and Hager, 1989)

The dimensionless discharge coefficient μ (Figure 2) is defined according to the following equations:

$$\mu_{\min} = 0.313\left[1 + \frac{1}{2}\left(\frac{H}{r}\right)^{1/3}\right], \text{ for } \theta_{\min} = -20^{\circ} \tag{6a}$$

$$\mu_{\max} = 0.483\left[1+\frac{1}{69}\left(\frac{H}{r}\right)^{1/3}\right], \text{ for } \theta_{\max} = 20^{\circ}\left[1+\frac{1}{2}\left(1-\frac{H}{r}\right)^{2}\right] \tag{6b}$$

$$\overline{\mu} = \frac{\mu_{\min}}{\mu_{\max}} \tag{6c}$$

$$\Delta = \frac{\theta - \theta_{\min}}{\theta_{\max} - \theta_{\min}} \tag{6d}$$

$$\frac{\mu}{\mu_{\max}} = \overline{\mu} + (1-\overline{\mu})\left[\Delta\, e^{1-\Delta}\right]^{4} \tag{6e}$$

One characteristic in the behaviour of this model is that it reproduces the observed two-limb curve of the discharge coefficient with H / r for a fixed θ: both in the descriptions by Bradley (1954) and Sinniger and Hager (1989) illustrated in Figures 1 and 2, for angles $\theta < \theta_{\max}$ the discharge coefficient increases for increasing H / r while for angles $\theta > \theta_{\max}$, the discharge coefficient decreases for increasing H / r. It can be shown by studying the partial derivative of function μ (6e) with respect to H / r that this trend is reproduced by the empirical model (6), but only for a limited range of values, i.e. $H / r \in [0.10;0.50]$ and $\theta \in [27°, 43°]$ (Figure 3).

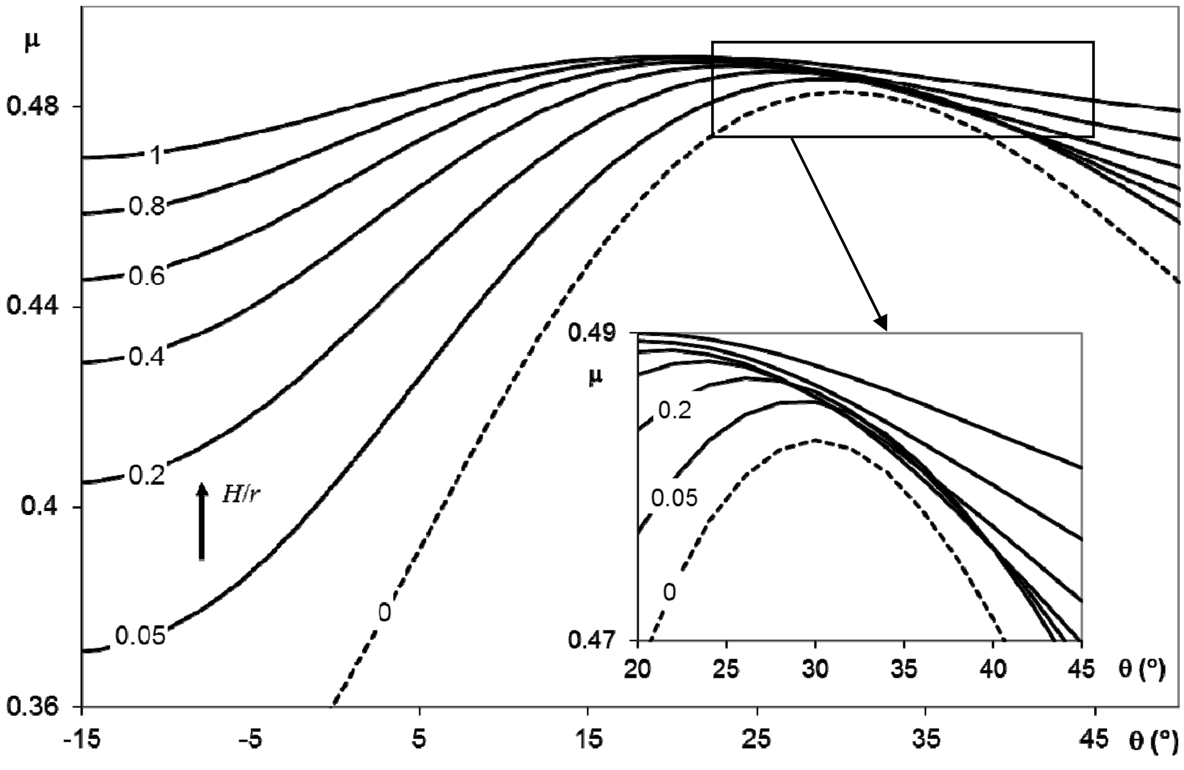

Figure 3. Discharge coefficient following Sinniger and Hager (1989)

In our study, we will focus on the model by Sinniger and Hager (1989). This model is based on the initial observations by Bradley (1954), as it considers a variable flap angle and thus appears more adapted to the actual gates of the River Meuse. However, the models by Chow (1959), Novak (1996) and Naudasher (1991) will also be considered in the comparisons with the experiments, to illustrate and highlight the strengths and weaknesses of each approach.

3 EXPERIMENTAL SET-UP

The La Plante dam is located near the city of Namur on the Meuse River (Figure 4). It is composed of four radial and flap gates (Figures 5 and 6). The physical model replicates a one-meter wide section of a gate of the La Plane dam at the scale $\lambda = 1/25$, including the design of the approach channel upstream and the stilling basin downstream the gate (Figures 6 and 7). The radial gate in the scale model is 0.141 m high, and the flap angle can vary between -33.36° and 65.24° (Figure 7) in order to reproduce the range of discharges considered in the River Meuse for flow over the gate.

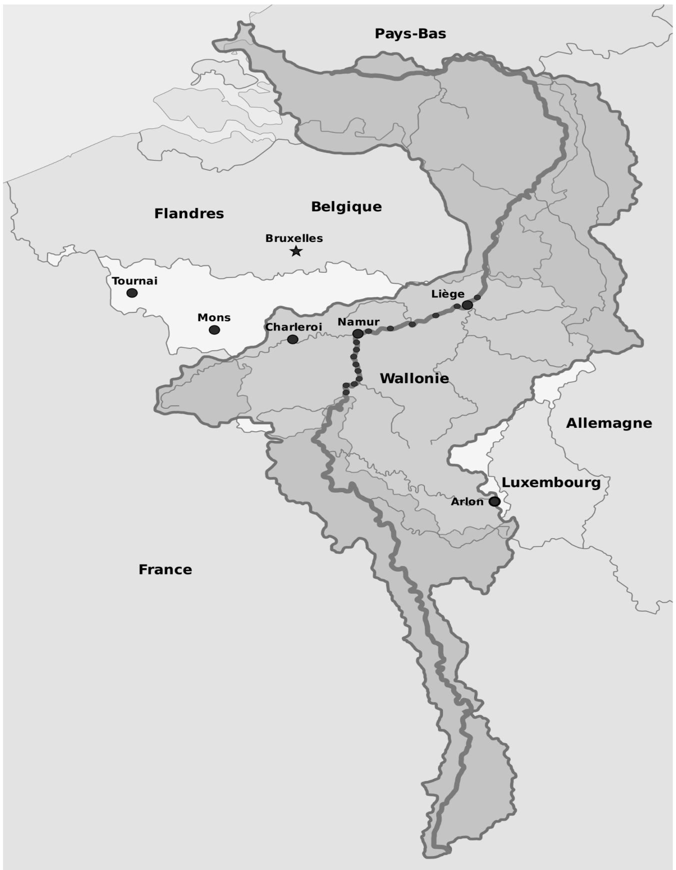

Figure 4. Overview of Meuse basin and river (fr.wikipedia.org)

Figure 5. View of the La Plante dam (GoogleEarth)

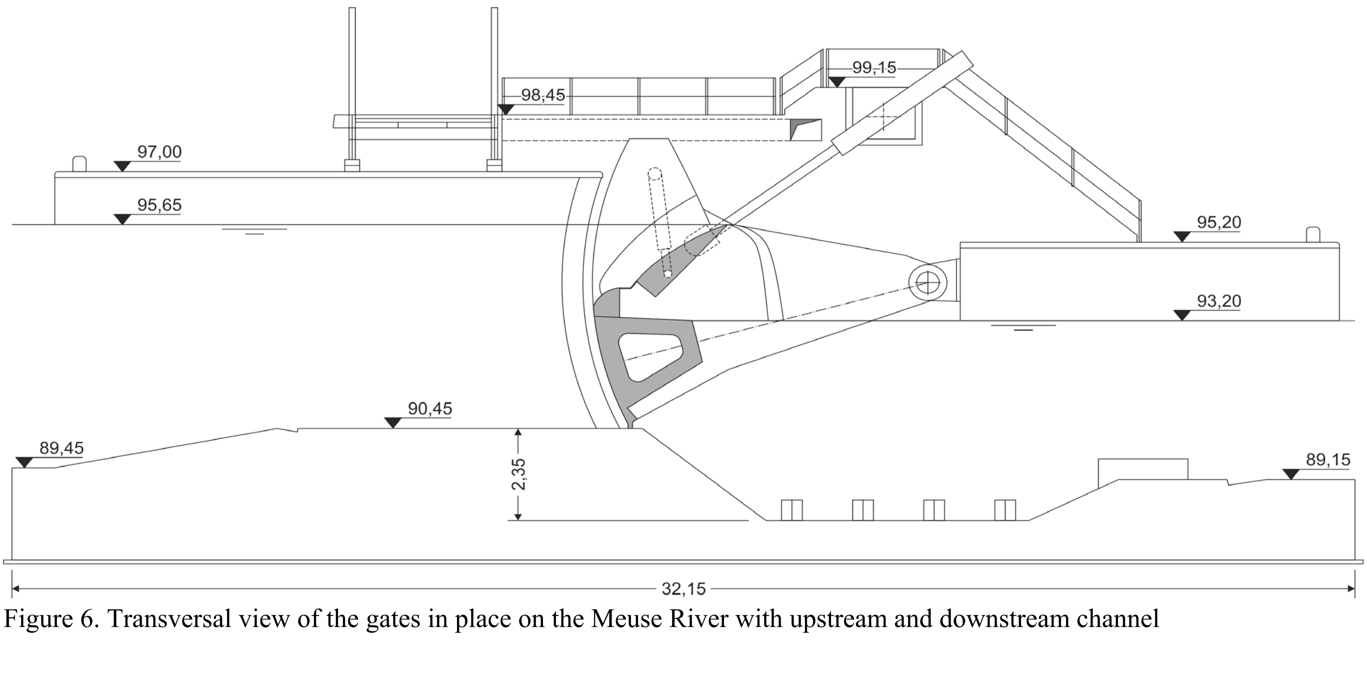

Figure 6. Transversal view of the gates in place on the Meuse River with upstream and downstream channel

Analysis of historical discharges and gate openings at the dam of La Plante showed that the maximum discharge occurring for a flow over the flap gate is about 300 m³/s. Above this value and to control the upstream level at a threshold of navigability, the radial gate starts opening and the water flows both over the flap gate and below the radial gate. When the discharge reaches 500 m³/s, there is no more flow over the flap gate, and the whole discharge flows below the radial gate only. For discharges higher than 800 m³/s, the radial gate is completely open resulting in an uncontrolled flow through the dam.

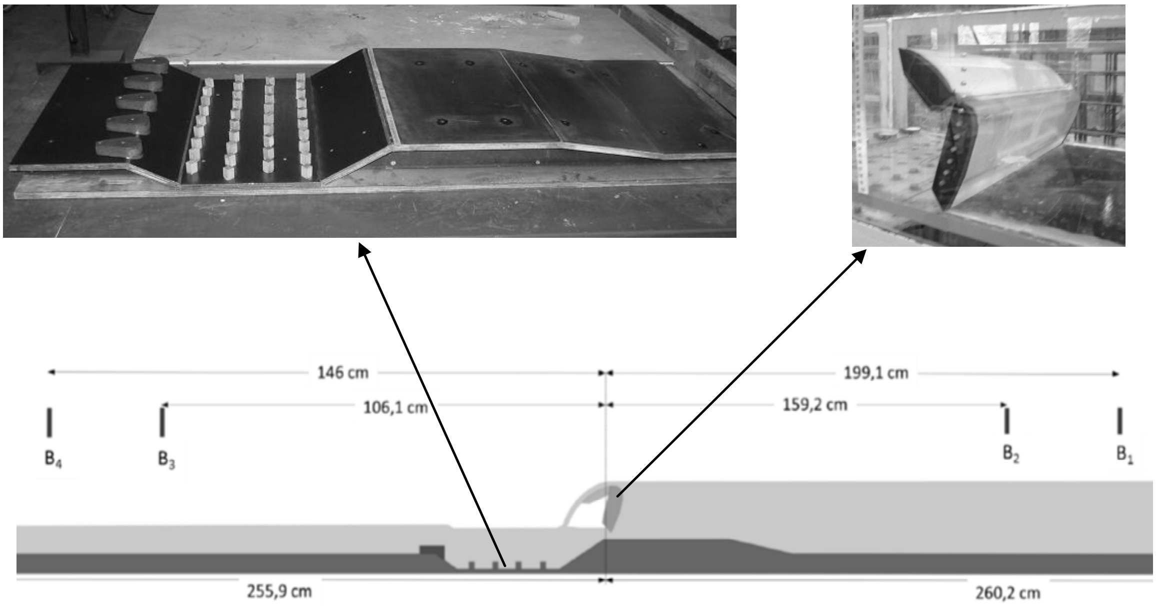

Figure 7. Experimental set-up

Using the Froude similitude to design the scale model, the scale factor for the discharge is $\lambda_Q = \lambda^{2.5}$. As the width of the prototype gate is 22.5 m, our physical model that is 0.495 m wide only represents a 12.375 m wide portion of the real gate. Accounting for the fact that the actual dam is composed of 4 gates, the scaled discharges are provided in Table 1. In the present study, we will focus on flow over the flap gate only, i.e. discharges up to 13.2 l/s in the scale model (300 m³/s in prototype).

The flume is equipped with 4 ultrasonic probes to measure the water level. The probes are located as indicated in Figure 7 at distances upstream and downstream from the gate equal to at least 3 times the maximum water depth in the channel. The discharge is obtained by an electromagnetic flow meter (ABB).

Table 1. Discharge ranges in the prototype and in the scale model

Type of flow	$Q_{prototype}$ (m³/s)	Q_{model} (l/s)
Flow over the gate only	0 – 300	0 – 13.2
Flow over and under the gate	300 – 500	13.2 - 22
Flow under the gate only	500 – 800	22 – 32.5
Uncontrolled flow	800 and higher	32.5 and higher

4 EXPERIMENTAL RESULTS

The experiments were conducted for 6 positions of the gate. The geometrical parameters are summarized in Table 2.

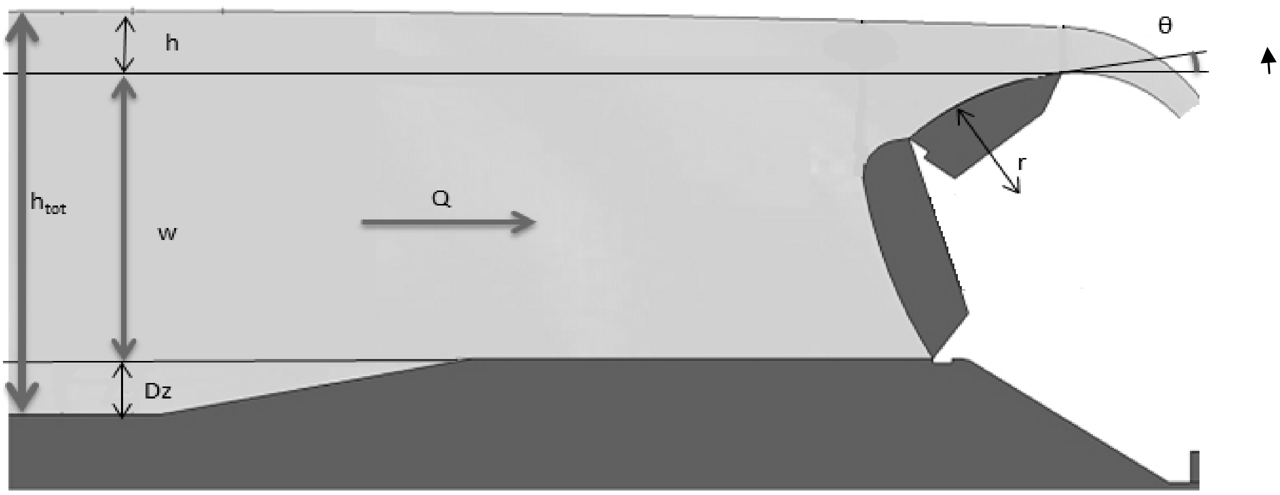

Figure 8. Sketch of the experimental set-up with geometrical parameters

Table 2. Geometrical parameters of the experimentation as shown in Figure 8.

Position	θ (°)	w† (m)	r (m)	Dz (m)	L (m)
A*	-33.36	0.142	0.180	0.0231	0.495
B	-19.89	0.148	0.180	0.0231	0.495
C	-5.97	0.164	0.180	0.0231	0.495
D	13.64	0.198	0.180	0.0231	0.495
E	35.57	0.228	0.180	0.0231	0.495
F	65.24	0.248	0.180	0.0231	0.495

* Lower position of the gate, w† is the position of the highest point above the gate toe level (lip of the gate in case of a positive θ, crest otherwise)

For each position of the flap gate, experiments were conducted by varying the inflow discharge and the upstream water level. The resulting measured discharges and water level were averaged over about 2000 values, acquired at a rate of 25 Hz. In order to compare the measured discharge coefficient with the prediction by the formula by Sinniger and Hager (1989), the measurements were grouped by ranges of H / r, as illustrated in Figure 9. For each range of considered values of H / r, the curves by equations (6) are indicated, together with the measured discharge coefficients (equations 4-5).

It can be observed that the general trend is well reproduced in the experiments; however the theoretical model overestimates the discharge coefficient. It should be noted that equations (6) are only valid for flap angles larger than -20°, while in our experiments the lowest angle was -33.36°.

The general trend given by both the empirical model (6) and the experimental results is an increase of μ with increasing H / r. For angles of the flap gate below θ_{max} (θ_{max} is between 25° and 28° depending on H / r), the difference between measured and predicted discharge coefficient is larger than for value of the angle above θ_{max}. For angles above θ_{max}, this difference significantly reduces. For instance for $H / r < 0.15$, the theoretical value of μ overestimates on average for the 2 results above θ_{max} the experimental value of μ by 5% while for the 4 results below θ_{max} we have an average overestimation of 25%. It must be noted that this difference of overestimation of μ, between value of the angle above and below θ_{max} is reducing for increasing H / r. For instance for H / r between 0.28 and 0.33, the average overestimation of μ for angles above θ_{max} is about 2 % while it is now 11% for angles below θ_{max}.

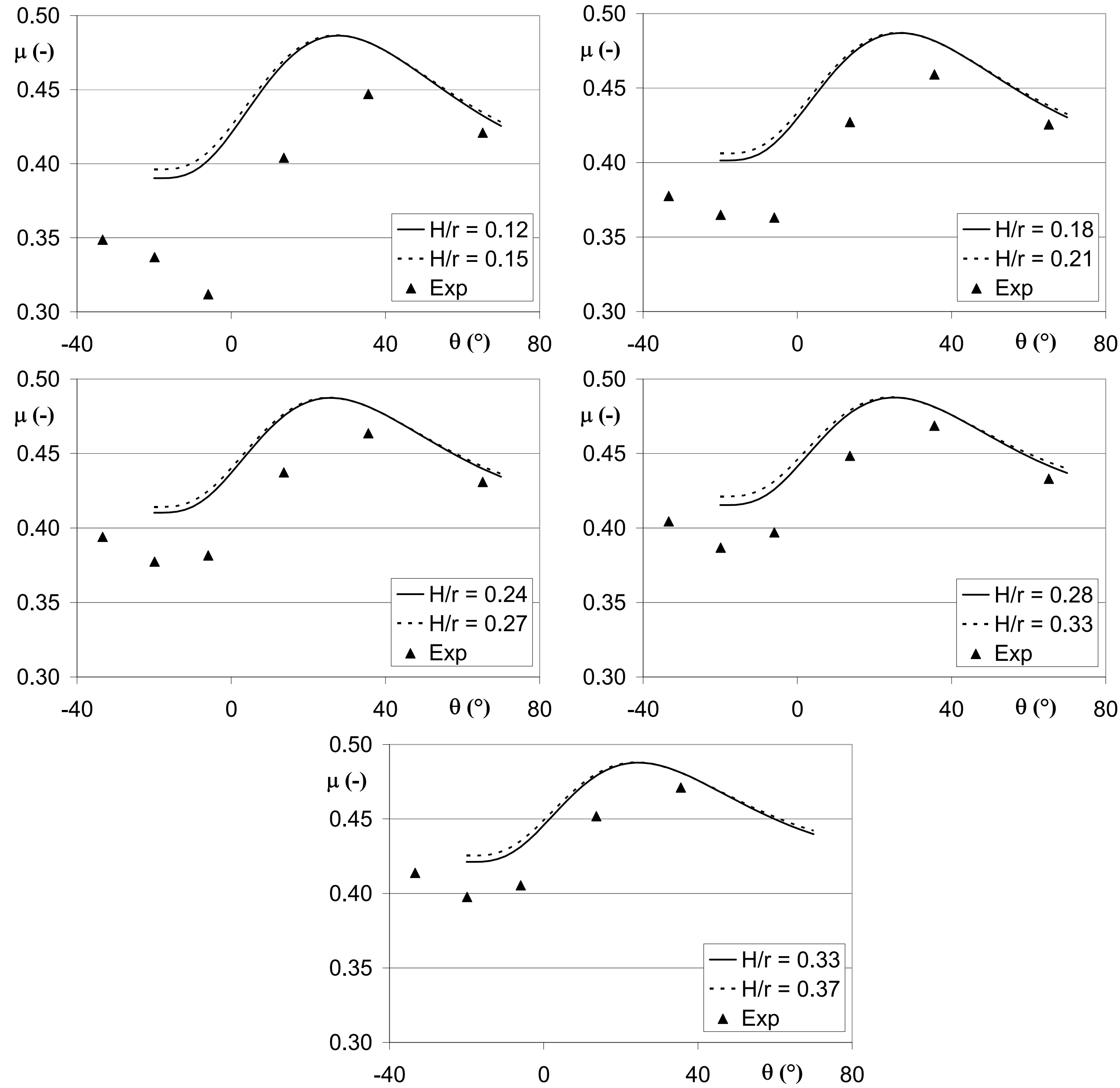

Figure 9. Discharge coefficient vs. θ (angle between the horizontal and the tangent to the downstream lip of the gate).
For $H/r > 0.33$ the measurement was not possible at $\theta = 65.24°$ due to too high upstream level compared to the channel design.

In order to analyze in greater detail the influence of gate flat position, the computed discharge coefficients from experimental results are compared to the models by Sinniger and Hager (1989), i.e. equations (6), Novak (1996) and Naudasher (1991). Figure 10 presents these comparisons for each position θ of the flap gate. The results obtained with the model proposed by Chow (1959) are very similar to those obtained with the model of Naudasher (1991) and were thus not included herein (i.e. the maximum differences on μ between both models is about 0.25 %).

The discharge coefficient in the formulae by Chow (1959), Novak (1996) and Naudasher (1991) do not depend on the flap angle. However, the experimental measurements clearly show a dependence on this angle, as already outlined before. This trend is well reproduced by the model of Sinniger and Hager (1989) that overestimates the discharge coefficient. For negative angles, the increase of μ with the upstream head represented by the ratio H / r is more influential than for higher angles of the flap gate. For high angles (above θ_{max}), the flap gate is closer to vertical. In this configuration, the radial gate and the flap are nearly aligned and the geometry of the entire gate is closer to that of a classical radial gate without a flap. This may explain why for the highest angle ($\theta = 65.24°$), the experimental results are in better agreement with the models by Novak (1996) and Naudasher (1991) than for lower position of the flap.

It should be noted that the best agreement is obtained with the formula by Sinniger and Hager (1989). For lower angles of the flap (below θ_{max}), the measurements tend to follow the formula by Sinniger and Hager (1989), but less closely. Also it can be noted that for higher values of H / r, the agreement between the experimental measurements and the predictions by means of the Sinniger and Hager (1989) formula improves.

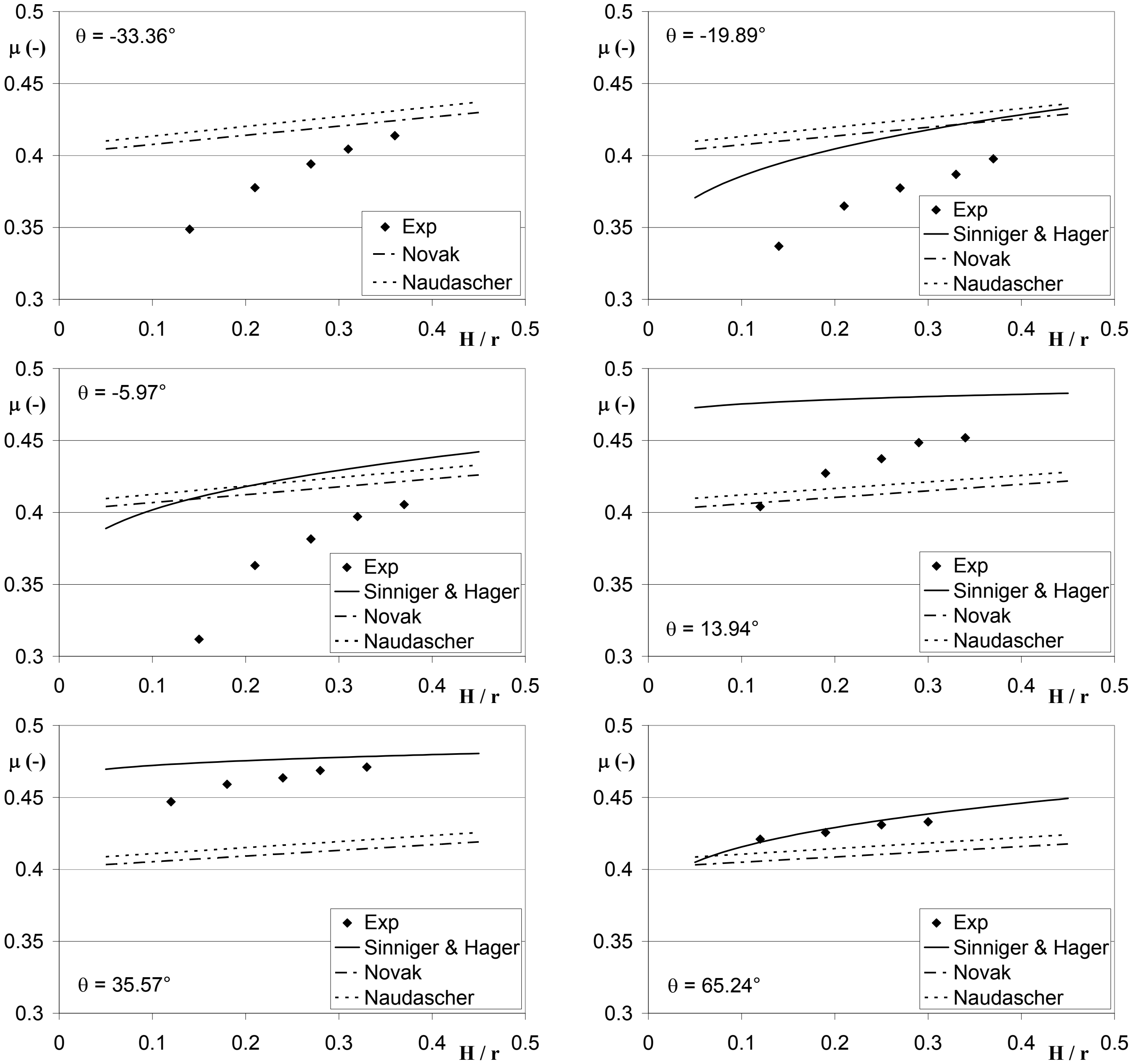

Figure 10. Discharge coefficient vs. upstream head

5 CONCLUSIONS

Experiments of flow over a radial gate equipped with a flap gate were presented. These experiments were conducted with the following objectives: (i) reproduce at a smaller scale a real gate at dams on the River Meuse in Belgium, and (ii) check the applicability of published empirical models to predict the discharge over such a gate. In the experiments, six positions of the flap gate were considered, and for each position, measurements were obtained for about five values of the discharges.

Among the existing formulae in the literature, the one proposed by Sinniger and Hager (1989) for drum gates appeared as the best suited, as it is the only one to the knowledge of the authors to account for a variable inclination of the flap gate. However, the comparisons between this model and the experiments showed that it is not completely adapted to our gate. Indeed, the formula always over-predicted the discharge coefficient. The reasons for these observed discrepancies could be the following. First, this formula was initially developed for drum gates that also present a variable angle. In the present case, we consider a radial gate with a flap gate. The approach flow might contribute to discrepencies, especially for low values of the flap angle. Another possible reason could be some local head losses arising from the scaled model.

Future work will be conducted by first carefully checking the scale model, then carrying out more experiments to complete the set of experimental points. Especially, it will be checked if for low angles, close to the $\theta_{\min}$ value of Sinniger and Hager (1989), a minimum of the discharge coefficient exists. Then, from this more complete set of experimental data, a new model for radial gates with flap gates could be developed.

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NOTATION

λ	scaling factor for distance
λ_Q	scaling factor for discharge
Q	Discharge
C	Coefficient of discharge in $ft^{1/2}.s^{-1}$
L	Width of the channel
H	Total head over the maximum point of the gate
θ	Angle of the tangent to the downstream lip of the gate with the horizontal
r	Radius of the gate (top mobile part)
g	Gravity acceleration
μ	Discharge coefficient (dimensionless)
μ_e	Experimental discharge coefficient (dimensionless)
μ_t	Theoretical discharge coefficient (dimensionless)

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