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Hydrodynamic forces during the operation of a model radial gate

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A 1:17 scale physical hydraulic model of a radial gate was employed to determine forces during the lifting and lowering of the gate with rates from 0.1 to 1.1 m/min for prototype (current operating rate is 0.1 m/min), and to determine the combinations of discharge, gate opening and tailwater level that cause instability of the gate. Forces were measured in trunnion bearing and in both hoists without restricting the movement of the model. Tailwater levels covered a wide range, representing the changed conditions after the completion of the downstream dam. The study indicated certain trends regarding the instability of the gate, and showed that the current rate of raising the gates could be significantly increased, providing safer operation of the whole system during some specific operating conditions.

Keywords: flume experiments; hydraulic model; hydrodynamic forces; radial gate

1. Introduction

This paper deals with a practical case of how operating conditions of an already constructed radial gate may change due to new downstream boundary conditions that result in an additional increase in lower pool elevation (tailwater level). Such influences may occur due to various reasons, for example, raising tailwater levels due to a construction of a new downstream dam or dam upgrading to increase existing reservoir capacity.

Radial gates have been a common water control structure for several decades. Recent improvements in their design and operation, as presented recently by Føsker (2015), prove their ongoing importance. The present study focuses on radial gates which are a part of the cooling water intake dam.

1.1. Description of the prototype

There are six radial gates installed at the prototype dam, each 2.2 m high and 15.0 m wide. Gates are made of steel and weigh 14.7 tons each. Gates are not designed as open trusses, but are box-designed, with circular-arc upstream skinplate covering also the downstream side of the gate body. The body is connected to both arms, which are box-designed as well. This means gate arms and body are enclosed hollow objects. When submerged, both arms are designed to remain watertight, while the body of the gate is designed to fill with water which penetrates circular holes in the bottom of the body. This results in the entrapment of an air pocket in the upper section of the submerged body, which is unwanted in terms of gate stability. However, boxed design has some considerable advantages. When discussing a similar design in terms of improvements achieved in the design and operation of radial spillway gates, Føsker (2015) recently stated that this design adds torsional stiffness, and also results in favourable size to weight ratio and less welding, compared to traditional open designed truss and girder gate bodies.

Each arm of the gate is 8.0 m long. The gate is raised or lowered at the rate of $v_{\text{lift}} = 0.1$ m/min by hoists that are attached to each arm at half the distance between the trunnion bearings (embedded in the downstream part of the piers) and the skinplate. Servomotors of the hoisting system are placed on a platform above the gate. In its closed position, the lower lip of the gate rests on the curved surface of the dam, 0.08 m below the dam's crest. As shown in Figure 1, gate opening z is given as a vertical movement of the gate's crest, while the tailwater h' is given as the downstream flow depth above the dam's crest.

1.2. Aim of the research

The aim of the research was to evaluate the effect of the much higher tailwater levels caused by the planned downstream dam – in contrast to the present state the gates are going to be submerged. Combined with certain discharges and gate openings the future conditions could cause instability of the gates. In the context of the paper presented, instability means dominant buoyancy. Instability range found in this investigation is a product of two effects: of buoyancy caused by trapped air in the gate body, and of hydrodynamic forces due to the flow.

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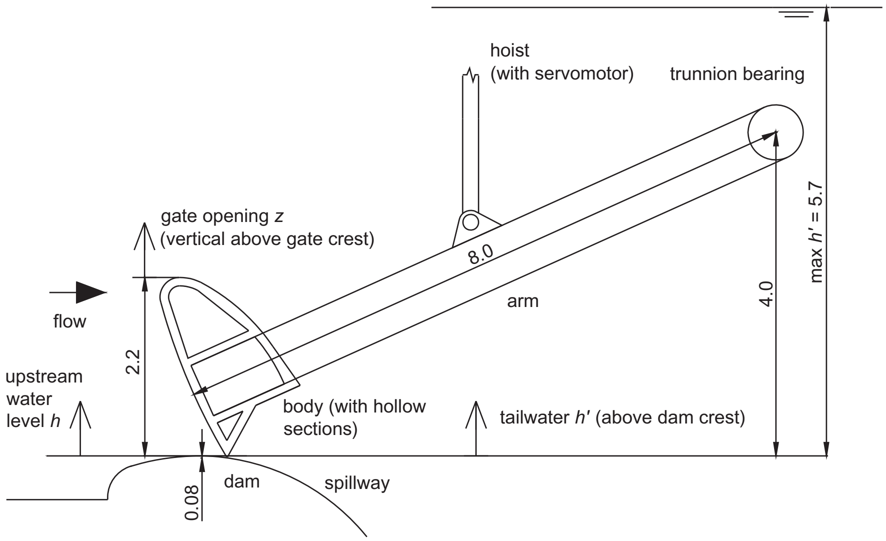

Figure 1. Definition sketch of a prototype radial gate above a curved dam. Dimensions in metres.

In the past, a case of gate lifting failure occurred and the present research examined whether the existing gates could safely be lifted faster, as that would ensure safer operation. This paper shows that the gate can become unstable under certain conditions during lifting or at fixed value of gate opening. The lowering of the gate was investigated as well, but to a lesser degree, since the gates are allowed to be lowered from raised position only at very small discharges. Lowering of the model gate into calm and relatively deep flow resulted in entrapment of air-pockets in the body of the gate, but did not represent any considerable danger to the operation of the gate.

1.3. Overview of similar studies

In contrast to various vertical sluice gates, which were considered in several fluid-structure-interaction studies, including Thang and Naudascher (1986), Kolkman and Vrijer (1987), Kolkman (1988), Aydin et al. (2006), Akoz et al. (2009), Dargahi (2010) and Erdbrink et al. (2014), radial gates received less consideration. Ishii and Naudascher (1992) proposed design criterion for dynamic stability of Tainter gates, and Ishii et al. (1994) investigated long-span gates, but both studies dealt with gates, which were not radial box-designed type.

Recently radial gates were investigated by Clemmens et al. (2003) (in terms of calibration), Bijankhan et al. (2011) (in terms of condition curves) and Anami et al. (2012) (in terms of hydrodynamic pressure fluctuations). The present study summarizes extensive experimental work on hydrodynamic forces during gate lifting and thus represents new data that should prove useful in future numerical models, design and operation of similar gates.

2. Materials and methods

2.1. Hydraulic model

The experiments were performed on a physical hydraulic model with a free surface (Froude similarity). Geometrically similar spillway with a gate and adjacent piers were constructed in 1:17 scale (undistorted model) and placed in a channel, 20 m long, 1.06 m wide and 0.7 m deep. The dam and stilling basin were wooden, while the gate and piers were made of Plexiglas. All parts of the gate were laser-cut out of 3 mm thick plate and then glued together to form a solid object. Both trunnion bearings were metal.

Hoists were 2 mm steel cables attached to a stiff crossbar that was raised or lowered with a servo drive. These cables could introduce some model uncertainty regarding rigidity. However, prototype hoisting equipment does not allow any upward forces in hoists, that is, $F_{\text{hoist}} \leq 0$ has to be strictly avoided, because such forces led to failure in the past. This makes prototype hoists in effect similar to model cables, which, of course, can only carry downward tensile load and no upward load.

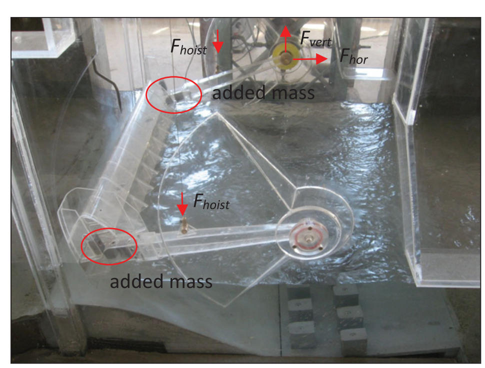

Figure 2. Side view of the 1:17 scale model with positive directions of measured forces.

Model sealing was performed with 3 mm rubber strings, attached to both lateral curved edges of the skin-plate. Thus seals covered very narrow gaps between the gate body and walls of the spillway piers. A series of measurements with and without those seals showed that their effect on measured forces was negligible.

To achieve the required similitude of both the mass and the centre of gravity, extra mass was added locally, as suggested by Novak et al. (2010), that is, several blocks of lead were placed symmetrically in both arms where the arms connect to the body, as in Figure 2.

2.2. *Measuring system*

The following measuring equipment was employed: electro-magnetic flowmeter to measure discharge, point gauges and pressure probes to measure water surface elevation (at three locations upstream of the gate and three locations downstream of the stilling basin), and strain gauges to measure forces in both hoists (500 N instruments, positive force F_{hoist} points downward) and in the bearing on the left side of the gate (1000 N instruments, positive horizontal component F_{hor} points downstream and positive vertical component F_{ver} points up). The latter were installed in a special steel frame just outside of the wall of the left side pier, as shown in Figure 2.

Pressure probes and strain gauges were calibrated at known water levels and known weights, respectively. It was confirmed that all strain gauges had linear response and their accuracy was 0.1% of their measuring range, that is, $\pm$ 0.5 and $\pm$1.0 N, which mean $\pm$2.46 and $\pm$4.91 kN for prototype.

National Instruments hardware (NI CA-1000) and software (Lab View Signal Express) were employed for data acquisition. In cases of fixed gate openings the recording of data lasted for 30 s. In cases of lifting/lowering of the gate data acquisition lasted for the duration of the manoeuver.

With the gate completely at rest on the dam crest the model hoists (i.e. steel cables) would bend and thus prevent accurate measurement of corresponding forces, thus the gate was considered as being completely lowered when the gate opening was not zero but minimal (z = 1.5 cm for prototype).

For every constant Q and constant z various h' were investigated. Tailwater levels were changed gradually within two separate sections so that values h' covered two separate intervals: (1) from $h' = 0$ upwards to $h' = h'_1$, where h'_1 means the tailwater level when the gate instability begins (i.e. h'_1 can be called the lower boundary of gate's instability for this combination of Q and z), and (2) from $h' = 5.7$ m downwards to $h' = h'_2$, where h'_2 means the tailwater level when the gate instability begins (i.e. h'_2 can be called the upper boundary of gate's instability for this combination of Q and z).

Measuring procedure to determine h'_1 was as follows: Firstly, the gate was positioned and forces were measured at $Q = 0$. Secondly, a constant Q was set and tailwater gate was adjusted to obtain h'. Increased h' increased upstream water level and also decreased Q. Thirdly, inflow valve was adjusted to obtain previous value of Q. Finally, measurement was performed when conditions settled. Measuring procedure to determine h'_2 was analogous, except that initial $h' = 5.7$ m was obtained at very low discharges and only then a desired Q was set, and levels h' were being gradually lowered.

3. Results and discussion

Taking into account the future conditions at the prototype dam, the following range of parameters were investigated

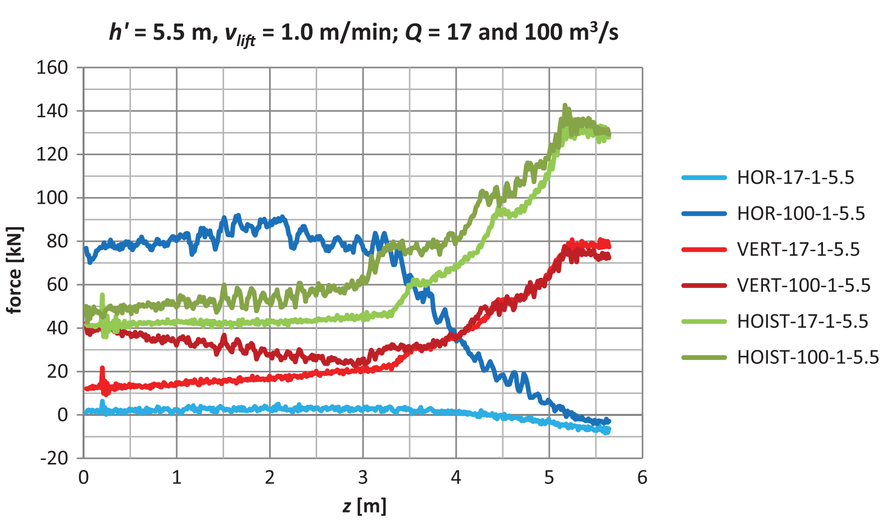

Figure 3. Forces during $v_{\text{lift}} = 1.0$ m/min at $h' = 5.5$ m for $Q = 17$ and 100 m^3/s. Denotations in the legend: force (HOR, VERT, HOIST) [kN]$-Q$ [m^3/s]$-v_{\text{lift}}$ [m]$-h'$ [m].

(from here onwards all parameters are given for the prototype, i.e. in nature):

- spillway discharge from 16.7 to 150 m^3/s (i.e. 100–900 m^3/s for all six spillways of the prototype dam),
- fixed gate opening 1, 25, 50, 75, 100 and 200 cm (but up to $z = 5.7$ m in cases of lifting the gate completely out of the water at maximal tailwater level),
- tailwater level from 0 to 5.7 m above dam crest (the latter being the maximum level after the completion of the downstream dam),
- lowering rate of 0.1 m/min, measured at hoists,
- lifting rates of 0.1, 0.4, 0.6, 0.8, 1.0 and 1.1 m/min, all measured at hoists.

The main results are given as graphs of average forces in relation to gate position z (i.e. cases of gate lifting, presented in Section 3.1), or in relation to tailwater depth h'

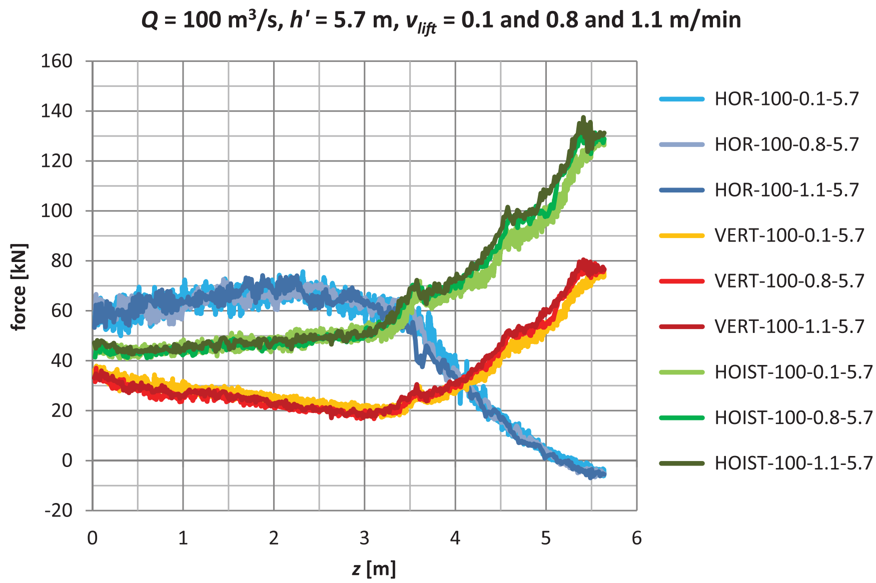

Figure 4. Forces at $Q = 100$ m^3/s and $h' = 5.7$ m for $v_{lift} = 0.1$ and 0.8 and 1.1 m/min. Denotations in the legend: force (HOR, VERT, HOIST) [kN]$-Q$ [m^3/s]$-v_{lift}$ [m]$-h'$ [m].

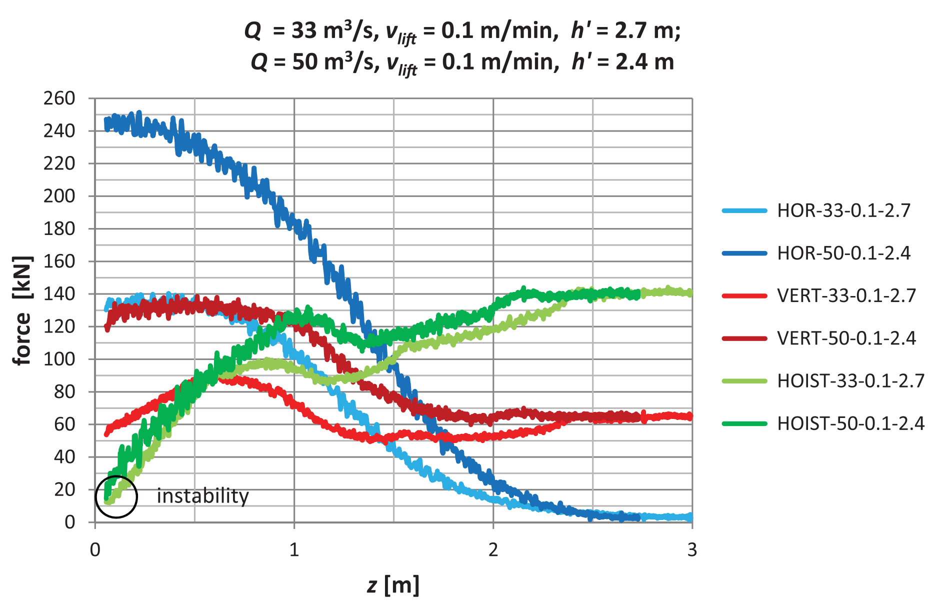

Figure 5. Examples of initially unstable gate becoming more stable during the lift. Denotations in the legend: force (HOR, VERT, HOIST) [kN]$-Q$ [m^3/s]$-v_{lift}$ [m/min]$-h'$ [m].

(i.e. cases with fixed gate position, presented in Section 3.2). As shown in Section 3.2, for a given discharge and a given gate opening various tailwater levels were investigated to determine combinations of Q, z and h' that caused gate instability. Here instability refers to conditions when the force in hoists is close to zero and gate displacements are evident (i.e. hoists vibrate or even bend, the body of the gate raises from initially lowered position and then lowers again, sometimes slightly and in other cases violently).

3.1. *The effect of lifting rate*

The effect of various discharges is presented in Figure 3.

Figure 3 shows that a significantly larger discharge resulted in significantly increased F_{hor} values (90 and 0 kN for $Q = 100$ and 17 m^3/s, respectively), while the corresponding increase of F_{ver} and F_{hoist} was much smaller. The effect of various lifting rates is presented in Figure 4.

Figure 4 shows that forces during $v_{\mathrm{lift}} = 0.1$ m/min were practically the same as during $v_{\mathrm{lift}} = 1.1$ m/min (for a given maximal discharge and maximal tailwater), indicating that the lifting rates in this range yielded practically the same effects (the difference between corresponding forces was mostly within ± 10 kN for nature). In general, lifting the lowered gates led to larger positive forces in hoists, which meant safer conditions (the conditions when F_{hoist} is close to zero must be avoided). This means that initially unstable lowered gate ($F_{\mathrm{hoist}} = 20$ kN at the start of the lifting) can become more stable as lifting proceeds, as shown in Figure 5.

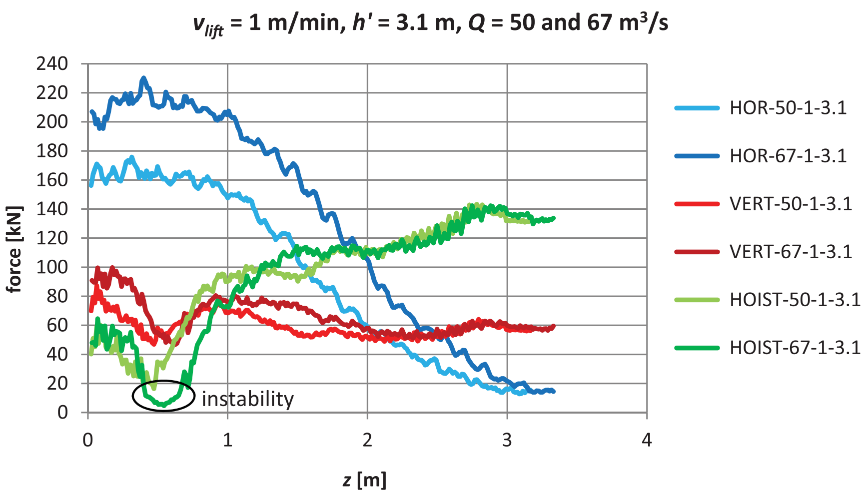

Figure 6. Examples of temporarily increased instability during the lift. Denotations in the legend: force (HOR, VERT, HOIST) [kN]$-Q$ [m^3/s]$-v_{\mathrm{lift}}$ [m/min]$-h'$ [m].

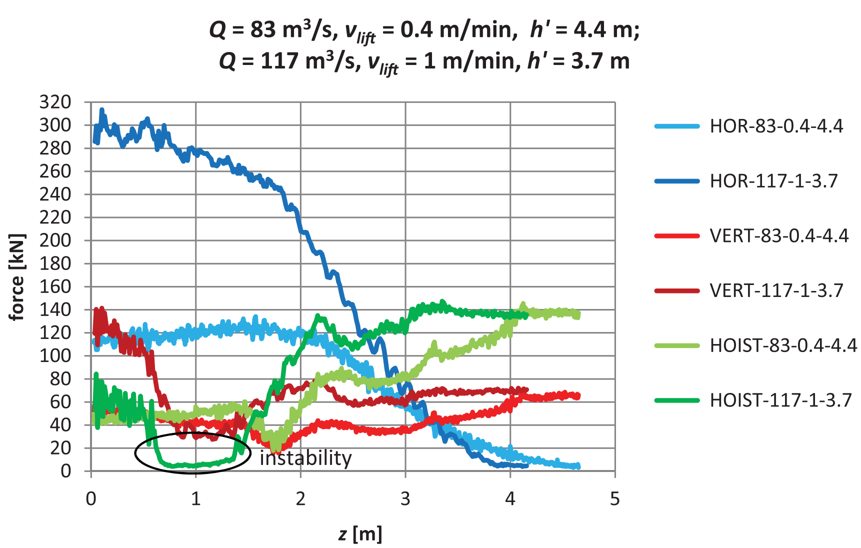

Figure 7. Examples of initially stable gate becoming temporarily unstable during lifting. Denotations in the legend: force (HOR, VERT, HOIST) [kN]$-Q$ [m^3/s]$-v_{\mathrm{lift}}$ [m/min]$-h'$ [m].

However, this beneficial effect of lifting did not always occur. Figure 6 shows some cases of initially somewhat unstable gate becoming *temporarily even more unstable* during lifting (i.e. instability increases during a certain part of the lift).

Furthermore, in some cases even initially *stable* gate can become unstable during lifting, as demonstrated in Figure 7.

The raise of partly or completely submerged radial gate means that there are different flow conditions appearing. These include flow over the obstacle (i.e. the gate), simultaneous flow under the gate and (unrestricted) flow over the gate, and finally only flow under the gate. With a constant inflow Q and a fixed position of the tailwater-regulating gate, the measured water levels h and h' indicated the following trends during the lifting of the gate: (1) h decreased and h' increased, especially when the initial tailwater level was low and the gate initially was not completely submerged. (2) In some cases with higher Q the water level just upstream of the gate undulated considerably and in some cases even vortices appeared, at least temporarily. A more detailed consideration of water level changes is beyond the scope of this paper.

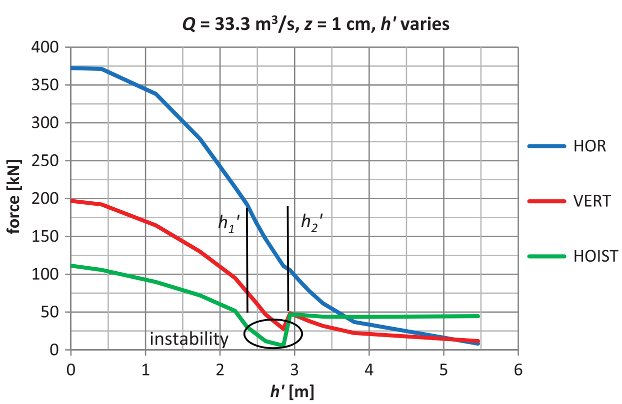

Figure 8. The effect of h' on forces for constant Q and z.

To summarize, the following can be said about the effect of lifting rate: Forces during lifting at 0.1 m/min are generally the same as during the lifting at 1.1 m/min. Initially unstable lowered gate can in some cases become more stable as lifting proceeds. In some other cases, however, initially stable gate can become unstable during lifting. This indicates that the range of conditions that cause instability needs to be determined, and these can be given as a combination of Q, z and h' (i.e. no v_{lift}), as described in Section 3.2.

3.2. Instability of the gate

Instability of the gate can occur even when the gate is not being lifted. With Q and z fixed at given values, the hydrodynamic forces changed considerably with increasing h'. In general, all measured forces decreased with increasing h' (i.e. the submerged gate became 'lighter'), in some cases so much as to cause the gate to become unstable (i.e. the gate 'floated' or 'drifted'). However, maximal h' did not necessarily mean greatest instability, as shown in Figure 8.

Figure 8 shows that the range of tailwater levels that cause gate's instability (i.e. interval between boundaries h'_1 and h'_2, see Section 2.2) can be determined quite clearly from the diagram of measured forces. When the gate becomes unstable, forces in hoists drop significantly and become almost $F_{\text{hoist}} = 0$. There is a corresponding 'notch' in F_{vert} diagram, while the corresponding change in F_{hor} diagram is very small. For $h' > h'_2$ values F_{hoist} remain practically constant. Figure 8 also shows that completely submerged gate (i.e. high values h') results in small forces, but stable conditions.

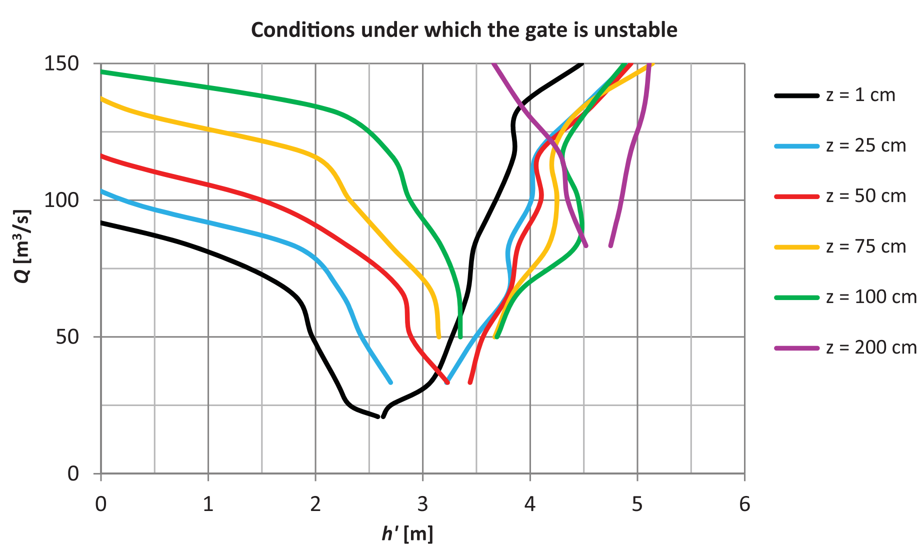

Figure 9. Combinations of Q, h' and z when the gate was unstable. Equally coloured pairs of lines, denoted $z =$ const., represent values h'_1 (to the left) and h'_2 (to the right side of diagram) for a given Q and z.

The combinations of Q, h' and z that caused gate's instability are summarized in Figure 9.

To summarize, the following can be said about the combinations Q, z and h' that cause gate's instability: The extent of interval (h'_1, h'_2) can be defined from diagrams of measured forces. These intervals tend to be larger for smaller openings of the gate and tend to increase with discharge.

4. Conclusions

Physical hydraulic model was used to investigate forces in a box-designed radial gate at various modes of gate operation. Based on the experiments the following can be concluded:

(1) The rate at which the gate was lifted did not affect the overall stability of the gate; hydrodynamic forces during lift at 0.1 m/min (for prototype) were practically the same as at 1.1 m/min. This means that the current rate of 0.1 m/min could be increased up to 1.1 m/min, which should allow proper response to larger gradients of water depths and thus safer operation during events of higher discharges and/or water levels.

(2) In general, lifting the lowered gates led to larger positive forces in hoists, which meant safer conditions (conditions when F_{hoist} is close to zero must be avoided). However, certain limitations apply, because the gate can become temporarily even more unstable during lifting. Based on measured forces, these limitations can be described in terms of discharge, gate position and tailwater level, as described below.

(3) The extent of conditions causing instability of the gate showed certain trends. At small openings this extent was greater than at greater openings, which means that the smaller openings represent greater risk of instability. This is in accordance with similar previous investigations. Greater opening of the gate resulted above all in higher values of the lower boundary of instability. At constant gate opening, the extent of unstable conditions increased with discharge, that is, lower boundary decreased and upper boundary increased with discharge.

(4) For high tailwater levels, when the gate was completely submerged, forces in hoists remained mostly much smaller than in the corresponding cases with low tailwater and the same discharge and gate position. This could be expected.

(5) In the presented case it is possible to keep the existing hydromechanical equipment in function, but with limitations to avoid conditions that cause instability. However, if the buoyancy effects caused by trapped air were removed, the range of gate instability would probably reduce significantly. A boxed gate design that allows for trapped air in the gate body is disadvantageous in situations with high tailwater levels.

Disclosure statement

No potential conflict of interest was reported by the authors.

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