

# Hybrid Modelling of a Filling and Emptying System of a Navigation Lock

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**ABSTRACT:** When an emergency stop at the inland navigation lock “Iffezheim” occurs, the closing of the roller wagon valves without any external force cannot always be guaranteed. The Federal Waterways Engineering and Research Institute (BAW) was commissioned to investigate this problem. With a 1D/3D hybrid model of the filling and emptying system of one lock chamber, the discharges in the culverts for different valve opening positions were determined. The CFD toolbox OpenFOAM was used to calculate the vertical forces acting on the roller wagon valves. Conducting a sensitivity analysis, it could be shown that small geometrical variations have a great influence on the forces. Furthermore, the investigation showed that the forces are very dependent on the width of the two gaps up- and downstream of the valves between valve and shaft. In this paper the engineering problems and the investigation strategy for the navigation lock “Iffezheim” will be presented. This includes the procedure for the 1D/3D hybrid modelling of the filling and emptying system with OpenFOAM and Flowmaster®. It will give an overview over a chosen practically orientated approach for solving these problems and the results will be discussed.

*Keywords:* OpenFOAM, CFD, Hydraulic structures, Lock, Valve

## 1 INTRODUCTION

Navigation locks serve the shipping to overcome height differences like they exist on dams. The navigation lock “Iffezheim” located close to the German city Baden-Baden at the river Rhine is one of Europe’s largest and most powerful inland navigation locks. It consists of two lock chambers with a length of 270 m and a width of 24 m. The maximum lift height is 12.50 m. For each filling, an amount of 77.000 m<sup>3</sup> water is needed. Every year about 30 million tons of cargo are transported through the lock.

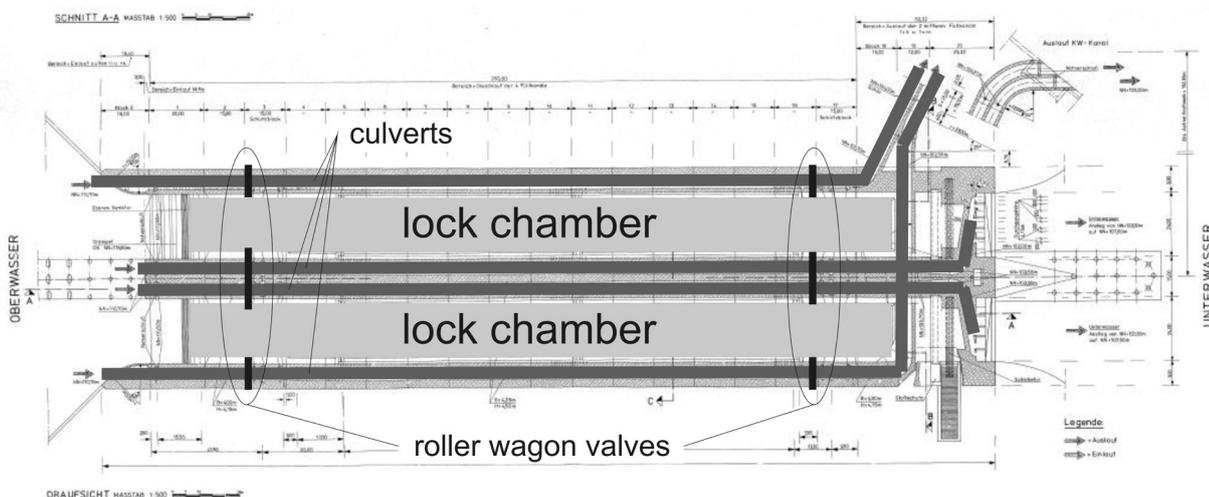


Figure 1. Footprint of the filling and emptying system of the lock Iffezheim

## 2 HYDRAULIC SYSTEM

The filling of the lock is operated through two longitudinal culverts at both sides of the chambers from the upstream outer harbour (Figure 1). These culverts are connected to the chambers by 960 filling nozzles (“Multiport System”). Emptying is carried out through the same culverts into the tailwater. The flow is controlled by two roller wagon valves at every culvert, one at the upstream inlet and another one at the downstream outlet. Opening the valves is performed by moving the wagon up in a shaft with a hydraulic cylinder. If the valves are opened partially, two small gaps at the upstream and at the downstream side of the gate (labelled as  $e_1$  and  $e_2$ , figure 2) open also and enable an additional flow above the gate.

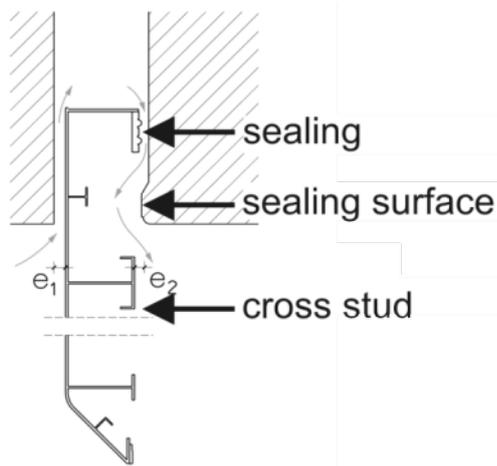


Figure 2. Roller wagon valve in the shaft with the upstream and downstream gaps

If, in case of emergency, the filling or emptying process has to be stopped before the target water level is reached (emergency stop), the roller wagon valves should close with a defined velocity to avoid a further water level change. This might occur if people go overboard or floating bollards are stuck. It is necessary that the roller wagon valves close without any external force, so that an emergency stop can be conducted in case of failure of the actuators, for example in case of power failure. The deadweight force ( $\sim 80$  kN) have to be big enough, that the gates can be closed without any additional external force.

In practice, performing the emergency stop safely cannot always be guaranteed: If the emergency stop is performed at about 30 % valve opening, it cannot be guaranteed that the valves close autonomously so that further water level rising or falling can be avoided. The Federal Waterways Engineering and Research Institute (BAW) was commissioned by the Federal Water and Shipment Administration (WSV) to investigate this problem.

## 3 HYBRID NUMERICAL MODELLING

For investigating this problem, a numerical model of the lock chamber and the filling system had to be created to understand the major hydraulic processes in case of an emergency stop. With a three-dimensional hydronumerical model small-scale phenomena like flow detachment or vorticity in the near field of hydraulic structures can be modelled. With increasing size of the domain, the computational costs increase. With an one-dimensional model larger domains can be modelled with a smaller level of detail. On the one hand small scale phenomena apart from the valves are not of interest for the investigation, so that a detailed model of the near field of the valves would be suitable. On the other hand the discharge in the culverts depends on the valve opening position and had to be determined. Next to the valve opening position this discharge depends on other hydraulic phenomena in the filling and emptying system of the chamber.

For investigating the vertical forces acting on the roller wagon valves a hybrid 1D/3D-hydronumerical simulation was conducted. This approach has already been used for former investigations at filling and emptying systems of inland navigation locks (Thorenz 2010). Therefore, a three-dimensional hydronumerical model of one valve was created. The investigations were performed for different valve opening positions. Changing the valve opening position influences the discharge in the culverts. Thus a one-dimensional hydro numerical model of one lock chamber with its filling and emptying system was created to determine the discharge for every investigated valve opening position.

### 3.1 1D Model

For determining the discharge occurring at different valve opening positions at different stages during the filling and emptying process, small-scale phenomena like flow detachment at corners are not of interest so that a 1D simulation of the chamber and the filling and emptying system is sufficient. Essentially, a navigation lock can be simplified as a reservoir with pipes connected to it. For modelling and simulating of such systems, the software Flowmaster® is often used. Flowmaster® is a commercial 1D Computational Fluid Dynamics (CFD) solution for the analysis of complex internal flow systems. It allows simulating system-wide fluid flow rates and pressure levels for the lock (figure 3).

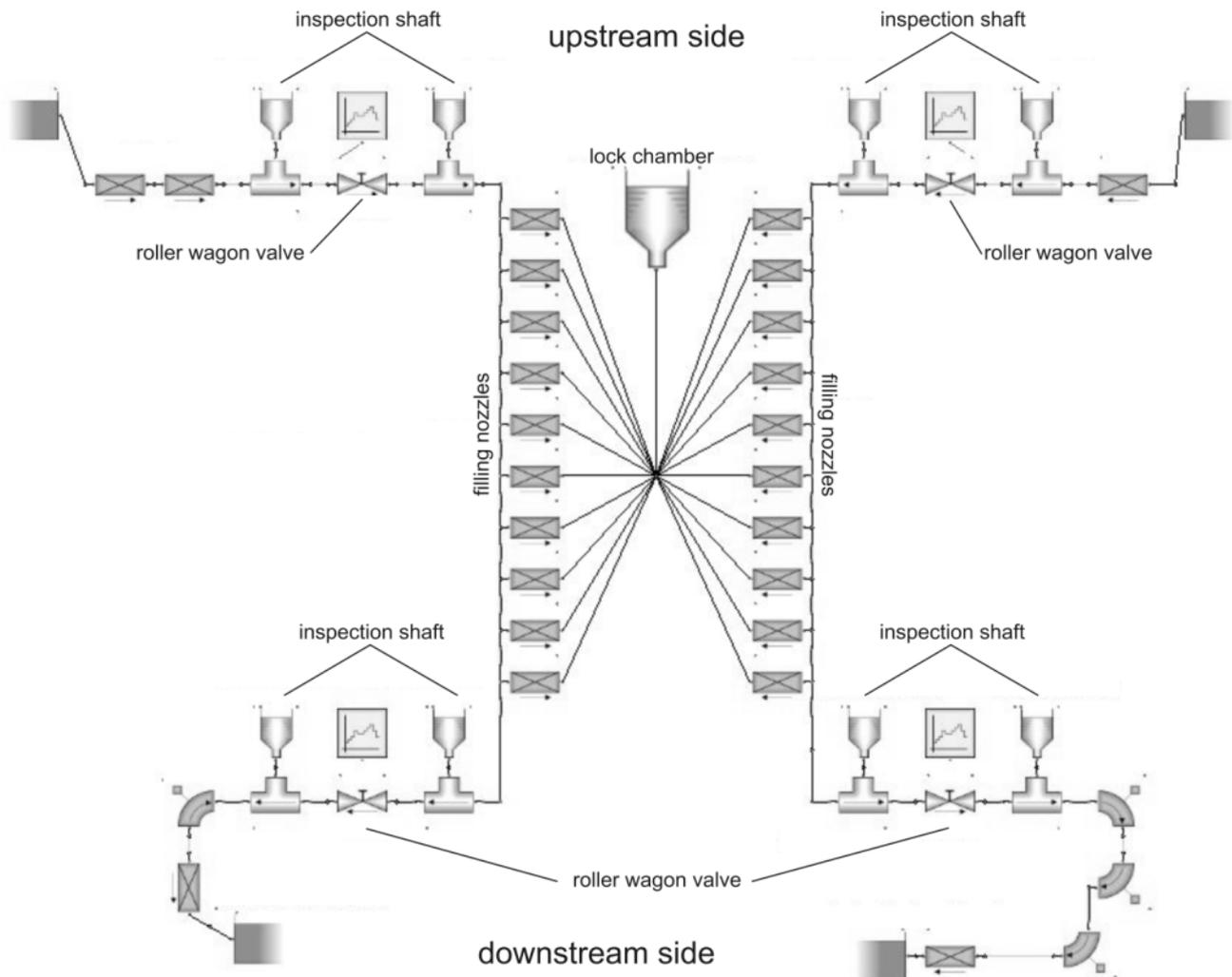


Figure 3. Abstract filling and emptying system as one-dimensional Flowmaster® network model

Many typical hydraulic components are available in the supplied libraries. These have to be parameterized with diameters, roughnesses or local losses. To find the necessary parameters, like the energy losses at the valves or the filling nozzles, multiple small scale 3D models of the individual parts of the lock were created (e.g. figure 4). The energy loss coefficients for the different internals were calculated according to Bernoulli's principle (equation 1):

$$\zeta = \frac{\Delta H \cdot 2g}{v^2} \quad (1)$$

where  $\zeta$  = energy loss coefficient,  $\Delta H$  = total headloss,  $g$  = gravity acceleration,  $v$  = velocity.

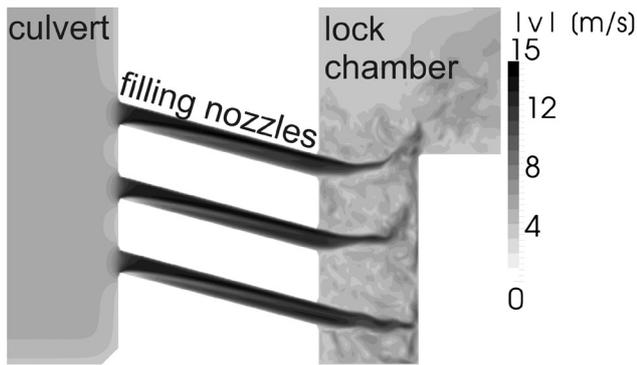


Figure 4: Computed velocity field in a cross-section of a 3D model of the filling nozzles

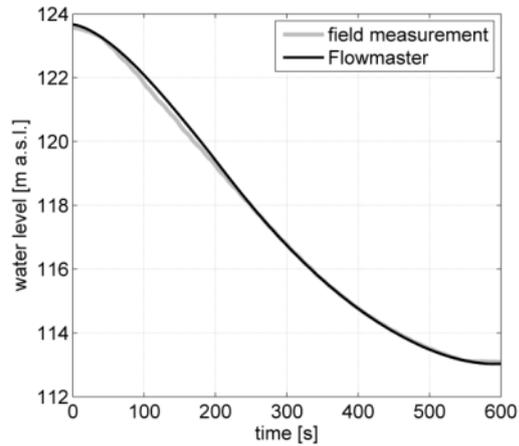


Figure 5: Comparison between measured lock water level development and computational results

Some loss coefficients were estimated due to values from standard literature. A final calibration was performed by a recalibration of the filling nozzles' loss coefficients and a comparison with field measurements (figure 5).

### 3.2 3D Model

The flow detachment in front of and behind the valves and in the gaps has large influence on the forces acting on the roller wagon valves. Therefore a detailed 3D model with a very high resolution in the regions of flow detachment was created to determine the vertical forces for different opening positions. The calculations were performed with the open source CFD toolbox OpenFOAM with the two phase transient solver interFoam (Rusche 2002). A detail model of a planar section of one culvert with one valve was constructed (figure 6). The model was 20 m long and had a width of 0.20 m. The base mesh size was 0.20 m. Areas where small-scale phenomena like flow detachment occur (e.g. the gaps between valve and the shaft) were discretized up to a mesh size of 0.005 m. Mesh generation was carried out with snappyHexMesh (Gisen 2014). For turbulence modelling a SpalartAllmarasIDDES model (Lysenko et al. 2013) was used. Three dimensional transient calculations with stationary boundary conditions were conducted until a quasi-stationary solution was achieved and the vertical forces acting on the roller wagon were probed. The calculations were performed on the computational clusters of the Federal Waterway Engineering and Research Institute. Numerical investigations with twenty different valve opening positions were carried out.

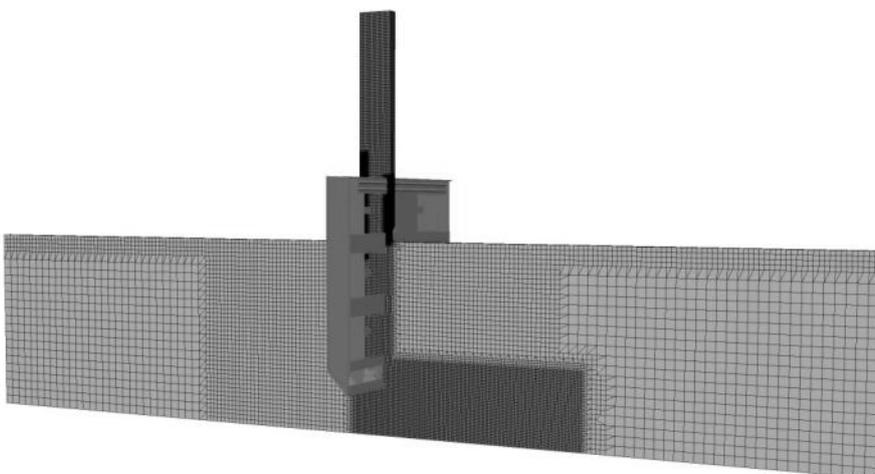


Figure 6. Mesh of the 3D hydronumerical model of one culvert with a roller wagon valve

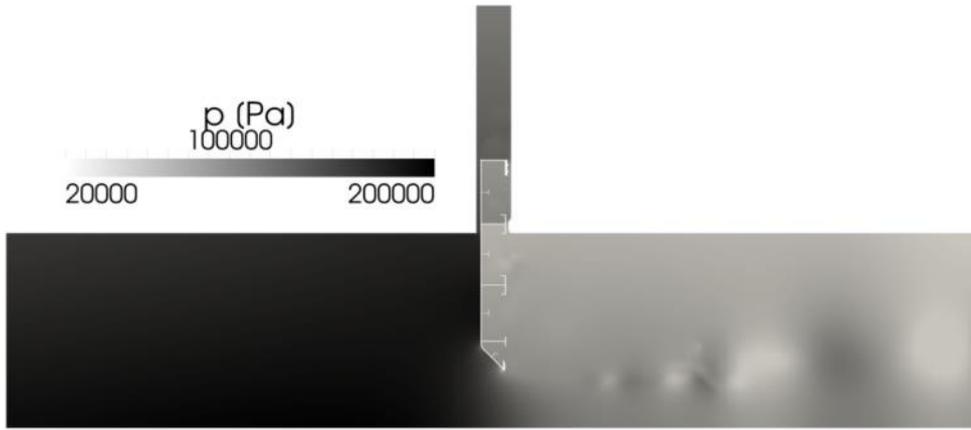


Figure 7. Pressure deviation for a valve opening width of 25 %

As boundary conditions for the inflow and the outflow boundary of the 3D model a stationary pressure was specified. For the velocity field, Neumann boundary conditions were applied. The forces on the valve were computed directly within OpenFOAM from the pressure and the shear stresses. Corresponding to the flow rates, which were determined with the 1D model, the forces acting on the roller wagon were scaled afterwards with the square of the flow rate ratio:

$$F_v = F_{OF} \cdot \left(\frac{Q_{1D}}{Q_{3D}}\right)^2 \quad (2)$$

where  $F_v$  = vertical force acting on the valve,  $F_{v, OF}$  = vertical force acting on the wagon (result of 3D model),  $Q_{1D}$  = flow rate in 1D model,  $Q_{3D}$  = flow rate in 3D model.

One exemplary pressure distribution for a valve opening width of 25 % is shown in figure 7.

## 4 RESULTS

### 4.1 General results

Performing twenty 3D calculations for valve opening positions between 2 % and 100 %, the vertical forces acting on the roller wagon during the whole opening process could be determined. The results of the investigation are shown in figure 8. Lifting forces are positive, forces acting downwards on the wagon are negative. The shown forces are an average over about 100 time steps after a quasi-stationary solution was reached.

Considering the results of the CFD calculations, the vertical forces acting on the roller wagon depend on the valve opening and in particular on the width of the two gaps  $e_1$  and  $e_2$ . With increasing valve opening the gap  $e_2$  increases and the flow above the wagon intensifies, which leads to decreasing pressure above the wagon and smaller downward forces. The investigation showed, that the forces are strongly dependent on the actual sizes of the gaps.

In principle the shape of the curve (figure 8) can be divided into three states:

- State I: Small opening width. Due to the discharge under the wagon, the pressure under the wagon decreases. The downstream gap  $e_2$  (figure 2) is still closed and the pressure in the shaft equals upstream pressure.
- State II: Further valve opening releases a gap at the downstream sealing line. Flow above the wagon occurs and the pressure above the wagon decreases. As a consequence, the forces acting downwards decrease.
- State III: At valve opening widths of about 30 % and 60 % the downstream gap  $e_2$  is reduced by the horizontal cross studs. Subsequently, the flow above the wagon decreases and the pressure increases. As a consequence, the forces acting downwards increase.

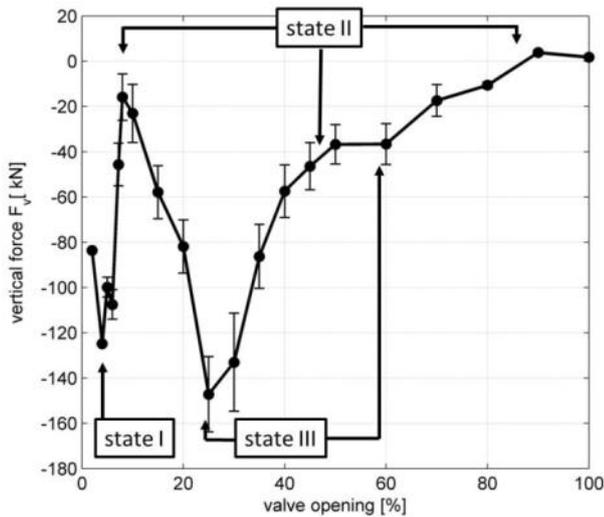


Figure 8. Vertical forces acting on the roller wagon for different valve opening positions

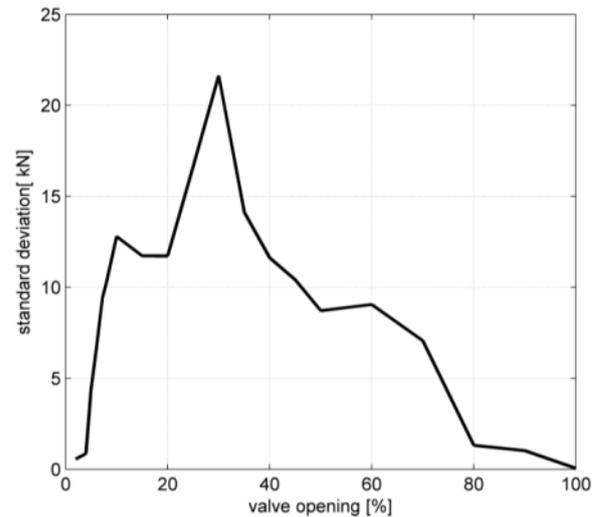


Figure 9. Standard deviation for different valve opening positions

Altogether, with this model no force could be determined being high enough to avoid an autonomous closing of the valves.

Regarding the forces over time shows a fluctuation around the average. Figure 9 shows the standard deviation of the measured forces. The highest fluctuation occurs at an opening with of about 30 %. In comparison with the high forces (150 kN) at this opening width, this fluctuation might hardly affects the closing process.

#### 4.2 Sensitivity

To quantify the influence of geometric variations on the vertical forces acting on the wagon for a critical range between 2.5 % and 25 % opening width, a sensitivity analysis was carried out.

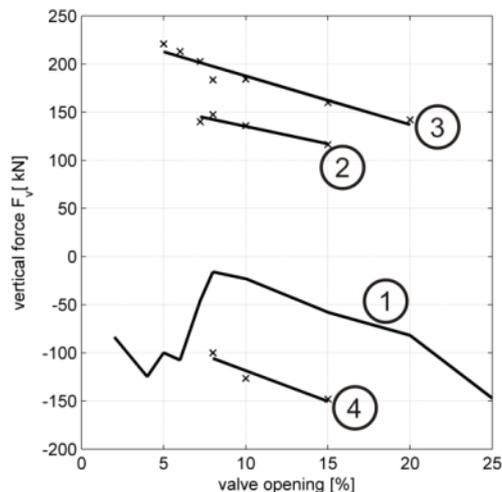


Figure 10. Vertical forces acting to the roller wagon for different geometrical variations

The results of this sensitivity analysis are shown in figure 10. Graph 1 illustrates the vertical forces for the original state without any geometrical variations (see figure 8). The result of a doubling of the downstream gap  $e_2$  can be seen in graph 2. This increases the discharge above the wagon and causes decreasing pressure in the shaft and smaller forces acting downwards. A closing of the upstream gap  $e_1$  avoids discharge above the wagon and leads to the results shown in graph 3. In this case the pressure in the shaft is almost equal to the downstream pressure. Thus, forces acting downwards to the valve are minimized.

This analysis shows, that the system is very sensitive to structural changes in the range of a few centimeters, as they can occur for example due to wear of the downstream sealing line.

Furthermore, the sensitivity analysis showed a basic correlation: The wider the upstream gap  $e_1$  and smaller the downstream gap  $e_2$  get, the bigger are the forces acting downwards to the valves.

## 5 IMPROVEMENTS

Regarding the results of the investigation, it can be seen that the vertical forces acting on the valves highly depend on the discharge through the shaft above the wagon. The goal of the investigation is to find a way to increase the forces acting downwards and to decrease the lifting forces, respectively. The solution must be robust enough, so that little structural changes do not affect the closing operation.

Closing the downstream gap  $e_2$  would be the most appropriate method. In this case, the pressure in the shaft would be almost equal to the upstream pressure and the forces acting downwards would be increased to the maximum. This solution cannot be realized due to constructive reasons.

However, another way to improve the situation is increasing the flow resistance by closing the upper field of the wagon with a steel plate (figure 11).

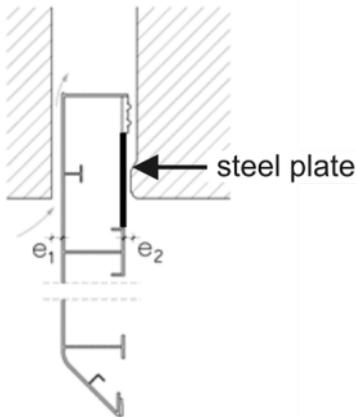


Figure 11. Constructive solution to increase the forces acting downwards

This solution was also investigated with the 3D numerical model. The results are shown in graph 4 in figure 10. It can be seen, that the resulting forces are strongly negative (downward directed forces). The implementation of the proposed solution can be realized on the wagon without changing other parts of the filling and emptying system and does not require any additional load.

## 6 CONCLUSION

When an emergency stop at the inland navigation lock “Iffezheim” occurs, the closing of the roller wagon valves without any external force cannot always be guaranteed. The BAW was commissioned by the WSV to investigate this problem. With a 1D/3D hybrid model of the filling and emptying system of one lock chamber, the leading discharges in the culverts for different valve opening positions were determined. The CFD toolbox OpenFOAM was used to determine the vertical forces acting to the roller wagon valves. Conducting a sensitivity analysis, it could be shown that small geometrical variations have a great influence on the acting forces. Furthermore, the investigation showed that the forces are very dependent on the width of the two gaps up- and downstream of the valves between wagon and shaft. With increasing width of the upstream gap  $e_1$  and decreasing downstream gap  $e_2$  the force acting downwards to the wagon increases due to higher pressure in the shaft. In contrast, the forces acting downwards to the wagon decrease with decreasing upstream gap  $e_1$  and increasing downstream gap  $e_2$ .

Regarding the results of the investigation, a robust solution was found, which inhibits the flow through the downstream gap by closing the upper field of the valve with a steel plate. This solution was investigated in the numerical model and the WSV is planning to try this solution on a prototype at the inland navigation lock Iffezheim.

## NOTATION

|            |                         |
|------------|-------------------------|
| $\zeta$    | energy loss coefficient |
| $g$        | gravity acceleration    |
| $\Delta H$ | total headloss          |
| $v$        | velocity                |
| $F$        | force                   |
| $Q$        | discharge               |

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