https://doi.org/10.71573/b2cfva89

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3D numerical modelling of interception efficiency of grate inlets with supercritical surface flow

Svenja Kemper [1] * https://orcid.org/0000-0002-5079-9215 & *Andreas Schlenkhoff* [1] https://orcid.org/0000-0002-5142-508X

[1]*University of Wuppertal, Hydraulic Engineering Section, Wuppertal, Germany*
**Corresponding author email:* s.kemper@uni-wuppertal.de

Abstract

Within the presented study 3D numerical model runs of grate inlets with supercritical surface flow conditions are done with the aim of expanding the knowledge of the street grate inlet capacity and the flow conditions that occur. Information of interaction processes from street to sewer are necessary to build up 1D/2D dual drainage models in order to get realistic information about urban flooding in case of intense rainfall events. Validation of the 3D model is done by use of laboratory results. The surface flow approaching the grate inlet with high flow velocities and small water depths can be simulated with good accordance to the measured results from laboratory. Major deviations occur in the intercepted flow rate and the water flowing over the grate. The analysis of the results allows the assumption that the deviations are probably caused by an insufficient calculation geometry.

Highlights

- Knowledge about the capacity of street inlets is necessary for 1D/2D dual drainage models.
- With 3D numerical models detailed information about interception processes can be achieved.
- Measurements from laboratory are necessary for validation of the 3D model.

Introduction

With regard to an increasing number of climate and weather extremes such as intense local rainfall events (IPCC, 2023), sustainable adaptions e.g. nature-based solutions or blue-green infrastructures are mandatory to improve the resilience of urban drainage systems. With 1D/2D dual drainage models the surface runoff, the sewer network flow and the exchange between both systems could be simulated and e.g. the effectiveness of nature-based solutions in reducing urban flooding could be quantified (Neumann et al., 2024). Following Cea et al. (2025) 1D/2D dual drainage models are from a numerical point of view the optimal choice to estimate the impact of urban pluvial flood events but a correct representation of physical processes (such as grate inlet capacity) is of high importance while investigating flood management applications.

Several investigations to quantify the capacity of specific grate geometries based on physical models exist, for example Gómez and Russo (2009) or Djordjevic et al. (2013). Russo et al. (2021) pointed out, that with a 3D model a better understanding of the hydraulics of the flow interception and the flow patterns approaching the inlet can be achieved. Three-dimensional numerical simulations of grate inlet capacity were done for example by Djordjevic et al. (2013), Gomez et al. (2016) or Lopes et al (2016).

The aim of the present paper is to validate a 3D numerical model to calculate the surface to unsurcharged sewer flow through grates with supercritical surface flow conditions caused by steep longitudinal slopes and therefore high velocities and small water depths.

Methodology

Numerical Model Setup

The CFD software FLOW-3D HYDRO v.2025.R1 was used for the presented numerical simulations. The model geometry consists of a flume with L_{Flume} = 10 m in length, W_{Flume} = 1.5 m in width and H_{Flume} = 0.2 m in height and a grate inlet on the left side in the downstream part of the flume. Within the presented study, two different grate geometries are investigated with general dimensions such as length of the grate L_G = 500 mm and width of the grate W_G = 500 mm (see Figure 1). The RANS (Reynolds-averaged Navier Stokes) equation are discretized by means of the Finite Volume Method (FVM) and the free surface is calculated with the Volume of Fluid (VOF) method (Hirt and Nichols 1981). The RNG-k-ε turbulence model was used within the described simulations which were calculated transient with a dynamically adjusted time step controlled by stability considerations. Mesh independency was proven with less than 2 % numerical uncertainty in the Grid Convergence Index while comparing flow velocities calculated with certain mesh resolutions defined by Celik et al. (2008). The final mesh size is for the basic mesh block MB1 in the x-y-plane $dx = dy$ = 8-12 mm and in height dz = 3 mm, for the nested mesh block MB2 (including grate) it is $dx = dy$ = 4mm and dz = 3mm.

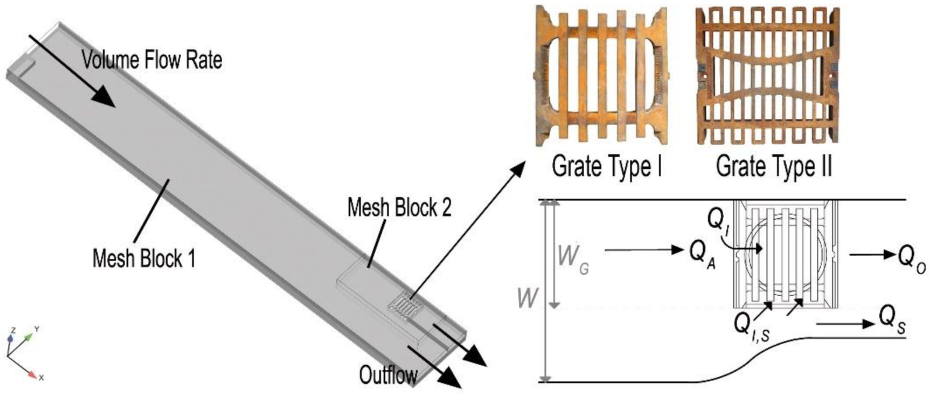

Figure 1. Numerical model setup and schematic sketch (plan view)

In Table 1 the investigated longitudinal (S_L) and transversal (S_T) slopes of the street as well as the total street runoff Q is given. Only supercritical flow conditions occur for all investigated discharges and slopes and therefore no backwater effects arise.

Table 1. Numerical Model Test Runs

Longitudinal Slope S_T [%]	2.5-10.0, $\Delta S_L = 2{,}5$ %
Transversal Slope S_L [%]	2.5
Total discharge Q [l/s]	3-21, ΔQ = 3 l/s

Physical Model Test Runs

To validate the numerical model, results from physical model test runs, described in Kemper and Schlenkhoff (2019), are used. The laboratory test runs were done in a full scale (1:1) model with the same geometric and hydraulic boundary conditions as in the numerical model. Water depths were measured with ultrasonic sensors upstream of the grate where steady as well as uniform flow conditions were already reached (resolution of the sensors: 0.18mm with a reproducibility of ± 0.15 %, General Acoustics e.K.). With platform load cells (Single Point Load Cell Model 1260, Tedea-Huntleigh), the volume of the water intercepted by the grate inlet Q_I [l/s], the side flow Q_S [l/s] as well as the water flowing over the grate Q_O [l/s] were measured over time. The total surface runoff is divided into three parts at the grate inlet with $Q = Q_I + Q_O + Q_S$. The intercepted flow rate on the length of the grate $Q_{I,S}$ is negligible in case of supercritical surface flow conditions, therefore it is $Q_A = Q_I + Q_O$ with Q_A =

approaching flow on the width of the grate. The separation of the flow rates Q_O and Q_S takes place downstream of the grate inlet with a separation wall in both models.

Comparison of numerical results with experimental approach

Surface flow conditions

Due to the investigated geometric and hydraulic boundary conditions only supercritical surface flow conditions occur within all test runs (Froude number $Fr > 1$). Furthermore, the water spread width W [m] upstream of the grate exceeds for all test runs the grate width, it is $W > W_G$. To validate the numerically modelled surface flow conditions upstream of the grate, the calculated and measured water depths are compared, see Figure 2 (left). The water depths upstream of the grate can be calculated within the 3D numerical model with good agreement to the measured water depths in the physical model with deviations less than 10 %. In addition to the water depths upstream of the grate, the occurring flow beside the grate is compared to validate the surface flow conditions calculated with the numerical model, see Figure 2 (right). Good accordance could be proven between the calculated and measured flow rates with deviations mainly less than 10 %.

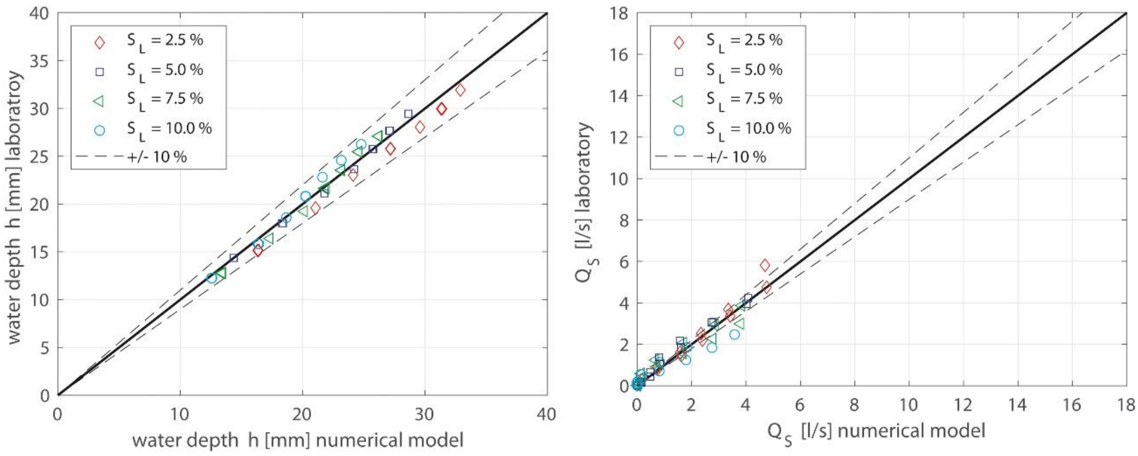

Figure 2. Comparison of numerical and experimental results: water depths upstream of the grate (left) and Q_S (right)

Grate Capacity

The grate capacity is defined by the interception flow rate Q_I. The numerically calculated intercepted discharge $Q_{I,num}$ is much smaller than the experimental achieved discharge $Q_{I,lab}$ and therefore the discharge flowing over the grate $Q_{O,num}$ is significantly greater than $Q_{O,lab}$ (see Figure 3). Major deviations of more than 10 % occur.

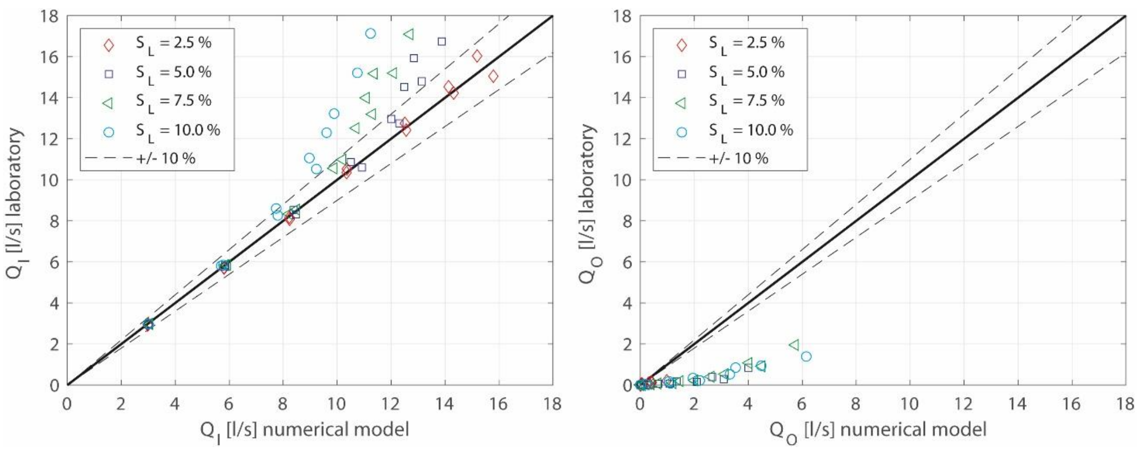

Figure 3. Comparison of numerical and experimental results: Q_I (left) and Q_O (right)

Results and discussion

With a transversal and longitudinal slope of the street, highly three-dimensional flow conditions appear at the grate. The general flow conditions of the approaching flow on the street can be simulated with good accordance to the physical model results. Major deviations occur in the interception flow rate where the numerically calculated capacity underestimates the measured capacity. The deviations increase with increasing flow velocities and therefore with increasing longitudinal slope and surface runoff. The deviations are not random but systematically, probably caused by modelling errors.

Even in the physical model as well as in the numerical model no influence due to the boundaries occur. In the numerical model no influence due to turbulence models could be detected, which coincides with Gomez et al. (2016). General geometric characteristics of the street and grate itself are mapped in the numerical model, but the discretization method (here: FAVOR™-method) in the numerical model leads to deviations in the model geometry compared to the laboratory model. Good agreement between numerical and physical model results with a simplified geometry fitting exactly to the mesh cells was proven in Kemper and Schlenkhoff (2018), which leads to the assumption, that the deviations are caused by an insufficient calculation geometry in the numerical model. As described in Kemper and Schlenkhoff (2019) among the approaching velocities and surface water depths the main influencing parameter for the grate capacity is the geometry of the grate itself. The present study emphasizes that even small geometric characteristics of the grate highly influence the interception efficiency.

Conclusions and future work

In order to investigate the street inlet capacity in detail to achieve realistic input data for 1D/2D dual drainage models and in particular for the interaction process from street to sewer, 3D numerical simulations were done with two different grate geometries and supercritical surface flow conditions. The validation of the numerical model by use of laboratory model results shows that the surface flow conditions with high velocities and small water depths can be simulated with good accordance to the measured flow conditions. Even in the interception flow rate and the water flowing over the grate major deviations occur systematically. Further investigations are necessary in order to reach reliable results with 3D models that are equivalent to laboratory results in quality and quantity with acceptable computing time durations.

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