Quantitative Research Based on Parametric Simulation of Waterlogging on Bridge Deck

Wenhao Cai1, 2, * and Ling Huang1

1Institute of Road and Bridge, Guangdong Provincial Academy of Building Research Group Co., Ltd. Guangzhou, Guangdong, 510500, P.R. China
2Department of Applied Mechanics and Engineering, Sun Yat-Sen University, Guangzhou, Guangdong, 510275, P.R. China
*Corresponding author’s e-mail: caiwenhao@gdjky.com

Abstract. With the rise of the bridge construction wave, the problem of waterlogging on bridge deck (WBD) also followed. The problems of WBD will cause serious economic losses, restrict the benign development of urban traffic and reduce the life quality of residents. The computational fluid dynamics (CFD) method is adopted to quantitatively research the WBD problem due to its high efficiency, low-cost and outstanding performance of visualization. In addition, four factors including rainfall, performance of the grates, mode of alignment change and disease characteristics have been parameterized simulated. In view of the influence of different factors on the WBD problem, corresponding suggestions in daily operation and management have been put forward in the present paper.

1. Introduction
As an important means of transportation, bridges have played an important role in improving residents' travel convenience and promoting social progress. However, more and more problems of waterlogging on bridge deck (WBD) continue to plague the bridge operation authorities. The problems of WBD not only caused serious economic losses and restricted the benign development of urban traffic, but also the corresponding improvement research is a major event related to people's livelihood and welfare. The followings are the main hazards of WBD:

Firstly, the WBD can cause early water damage such as chipping, peeling, potholes, and looseness of the asphalt surface, which affects the durability of the structure [1]. Liu [2] shows that different water damages will occur in whether the northern arid areas or the southern rainy areas, indicating that the WBD is the "big enemy" of asphalt materials. Secondly, the stagnant water will penetrate into the structure through the cracks and corrode the rebar, reducing the strength of the concrete structure [3]. Thirdly, when the bridge deck is under waterlogging, the splashing water produced by high-speed cars will seriously affect the sight of the drivers behind and increase driving risk [4-5]. Lastly, the stagnant water can significantly lead to traffic congestion, and seriously affects the improvement of residents' happiness [6-7].

There are many factors that affect the WBD, and they are researched by a lot of domestic and foreign researchers.

Li et al. [8] believe that there are three main reasons for the WBD problem, namely, unreasonable design of gully, unreasonable design of longitudinal or cross slope of bridge deck and insufficient design and construction of drainage facilities. Wen et al. [9] have drawn the flow-path diagram of the
straight-line slope section and the bottom of concave vertical curve utilizing the modified Manning’s formula, and the results show that when the cross slope remains unchanged, the larger the longitudinal slope, the longer the rainwater flow path and the deeper the WBD. Liang [10] carried out the hydraulic calculation of the curb-opening gully according to the calculation method of the gutter and grate gutter flow proposed by the US Federal Highway Administration. KHAN et al. [11] studied the cross slope and drainage problems in the design of multi-lane highways, their research results show that the cross slope and road width are the two most important variables for reducing the depth of standing water. Ressel et al. [12] believed that the geometric characteristics of roads have a greater impact on the length of rainwater flow paths. Road turns are usually accompanied by changes in cross slope, and rainwater flow paths vary in length on different lanes near the zero-cross-slope position, which affects the flow of rainwater on the road. Among those factors, the gully is one of the important factors affecting the WBD. The Department of Transportation of Texas in the United States has done a detailed study on the hydraulic characteristics of different types of gutters, see literature [13-14].

Currently, there are many methods to study WBD problems, such as empirical formula method [15], seed-spread algorithm [16], kinematic wave method [17], PAVDRN-code [18] and numerical simulation methods [19]. Among those methods, computational fluid dynamics (CFD) method (one of the numerical simulation methods) is favored by more and more researchers due to its high efficiency, low-cost and outstanding performance of visualization. Therefore, this work is devoted to the quantitative research of WBD problem by CFD method, focusing on the parametric research of the different factors including rainfall, performance of the grates, mode of alignment change, and disease characteristics.

2. Method

2.1. Basic governing equations

The basic governing equation of fluid motion is composed of mass conservation equation and momentum conservation equation, which is the well-known Navier-Stokes equation. For incompressible homogeneous viscous fluid, the governing equation can be expressed as follows:

$$\nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} + \mathbf{F}_b$$

Where \( \mathbf{v} \) is the velocity, \( \rho \) is the density of fluid, \( p \) is the pressure, \( \nu \) is the kinematic viscosity, \( \mathbf{F}_b \) is the body force per unit mass (usually referred to as the acceleration of gravity \( g \)), respectively.

2.2. VOF model

The problem in the present paper involves the rainwater flowing in the air which is an impermeable two-phase flow problem with interfaces. The Navier-Stokes equation will be solved simultaneously in air and water, and the kinematic interface is tracked by the VOF (volume of fluid) method:

$$\frac{\partial F_q}{\partial t} + \frac{\partial}{\partial x_i} (F_q u_i) = 0 \quad (q = 1, 2)$$

$$F_1 + F_2 = 1$$

Where, \( F_q \) is defined as the fraction of the volume occupied by the \( q \)-th phase of fluid in the cell to the total volume of the cell, since the problem of WBD in present work has only two phases, i.e., air and water, so \( q = 1, 2 \).

In the VOF method, the physical parameters are determined by the physical parameters of each phase in the control volume and the volume fraction function of each phase, that is, the physical parameters \( \varphi \) in the control volume are calculated by the following formula:

$$\varphi = \varphi_1 F_1 + \varphi_2 F_2$$
2.3. Turbulence model

The RNG $k-\varepsilon$ model is a two-equation model derived from the standard $k-\varepsilon$ model, using a statistical method called renormalization group theory. Turbulent kinetic energy $k$ and turbulent energy dissipation rate $\varepsilon$ can be obtained by the following transport equation:

$$
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k
$$

$$
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1k} \frac{\varepsilon}{k} (G_k + C_{3k} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon
$$

Where, $G_k$ represents the turbulent kinetic energy due to the average velocity gradient, $G_b$ represents turbulent kinetic energy due to buoyancy, $Y_M$ represents the contribution of the floating expansion of compressible turbulence to the overall turbulent dissipation rate, $\alpha_k$ and $\alpha_\varepsilon$ represent the inverse-effect Prandtl number of $k$ and $\varepsilon$ respectively, and $\alpha_k = \alpha_\varepsilon \approx 1.393$. The several default constants are $C_{1k} = 1.42$, $C_{2\varepsilon} = 1.68$, and $C_{3\varepsilon} = 1$. $S_k$ and $S_\varepsilon$ are user-defined source items respectively.

3. Model and Configuration

A benchmark model is shown in Figure 1, the full-scale size of a section of straight bridge deck is 100m×12m×0.5m, the longitudinal slope and cross slope are 1% and 2%, respectively, and the interval distance of the rainwater grate is 10m. Boundary condition (BC) of the upstream is set as massflow inlet according the different rainfalls, BCs of the downstream and the sky are set as pressure outlet, BCs of the curb and the bride deck are set as wall, and BC of the center line is set as symmetrical boundary. The rainfall in the computational domain is given by adding the mass source term in the governing equations, besides, during the calculation process, the water level monitoring points are set near the 5 grates.

It should be noted that the model in this work is scaled by 0.1 due to the limitation of grid amount and calculation efficiency.

![Figure 1. Schematic diagram of computational domain and boundary conditions.](image)

4. Results and Discussion

4.1. Effect of rainfall

According to the relationship between rainfall intensity and rainfall level, the drainage capacity of the gutter with a shallow triangular section can be calculated as follows:

$$
Q = 0.377 \frac{1}{i_n} h^\frac{8}{3} T^\frac{1}{2}
$$
Where, \( i_c \) is the cross slope, \( n \) is the roughness factor and \( n = 0.016 \) for asphalt road, \( h \) is the maximum water depth design value, \( I \) is the rainfall intensity. Substitute the known conditions into the above formula and scale it proportionally, we can obtain the different upstream inlet flow parameters, 1L/s, 2L/s and 4L/s, which is including the rainfalls. The depth of water accumulation at each monitoring point under different rainfalls is shown in Figure 2.

![Figure 2. Water depth at each monitoring point under different rainfalls](image)

The results indicate that when the inlet flow rate changes from 1L/s to 2L/s and from 2L/s to 4L/s, the change of the latter is twice as much as that of the former, however, the change in water depth has not doubled, which shows that the interception efficiency of the grates increases significantly with the increase of rainfall, in other words, improving the interception efficiency of the grates plays a key role to solve WBD problem.

### 4.2. Effect of performance of the grate

With the increase of the service life and the blockage of silt and garbage on the bridge deck, the performance of the grates will face different degrees of performance reduction. ANSYS fluent provides a way to simulate such a performance reduction, the porous media equivalent method. The degrees of grate performance reduction is replaced by different porosity. In this section, two cases with porosity equal to 1 and 0.5 have been investigated. The depth of water accumulation at each monitoring point under different performances of the grate is shown in Figure 3.

![Figure 3. Water depth at each monitoring point under different performances of the grate](image)
For the normal grates (porosity = 1), the water depth continues to drop as the water flows forward downstream. However, for the blocked grates (porosity = 0.5), the water depth remains almost constant as the water flows forward downstream.

4.3. Effect of mode of alignment change

During the operation of the bridge, the alignment of the bridge deck will change due to various factors, such as uneven settlement of bridge foundation, destruction of deck pavement and load of heavy vehicle. Four different modes of alignment change (named by type I, II, III and IV) under \( \dot{Q} = 1 \text{L/s} \) have been investigated in the present work, and they are shown in Figure 4.

The depth of water accumulation at each monitoring point under different modes of alignment change is shown in Figure 5. It can be found that the depth of water accumulation under different modes of alignment change is very different from each other, which reminds us that in the daily operation and maintenance process, attention to the alignment changes of the bridge deck cannot be ignored.

![Figure 4. Four different modes of alignment change](image)

![Figure 5. Water depth at each monitoring point under different modes of alignment change](image)

4.4. Effect of disease characteristic

During the operation period, the bridge deck will face many diseases, such as chipping, peeling, potholes, and looseness of the asphalt surface, this section will only introduce the effect of pothole disease. The potholes of the bridge deck are replaced by a characterized cubic subsidence, as shown in Figure 6. Each characterized cubic subsidence has the size of 6m×2m×0.1m.
Figure 6. A kind of characterized cubic subsidence to characterize pothole disease

The depth of water accumulation at each monitoring point under the pothole disease is shown in Figure 7. The results show that when potholes appear on the bridge deck, the depth of water accumulation is shallower than that without potholes under the same rainfall, which is because the pothole can effectively intercept part of the stagnant water. However, the negative effect is that the spread of accumulated water under the case of pothole becomes wider, which can be shown in the magenta region in Figure 8.

Figure 7. Water depth at each monitoring point under the pothole disease

Figure 8. Water depth at each monitoring point under the pothole disease

5. Conclusions

According to extensive literature research and in-depth investigation and analysis, we have concluded that the main factors affecting the WBD problem include rainfall, performance of the grates, mode of
alignment change, and disease characteristics. The quantitative research based on parametric simulation has been carried out by CFD method, and the main conclusions of this article are as follows: Firstly, the ultimate factor that affects the WBD is the performance of the grates, and improving the interception efficiency of the grates plays a key role to solve WBD problem. Secondly, when the grates are blocked, the water depth remains almost constant as the water flows downward, namely, the interception efficiency of the grates at different locations at this time are approximately equal. Thirdly, alignment change has a great impact on WBD problem, so it should be paid more attention during the daily operation and maintenance. Lastly, although the pothole disease can reduce the depth of stagnant water to a certain extent, it increases the spread of stagnant water, therefore, potholes must be repaired in time.

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