Study on hydrodynamic characteristics and influence factors of asphalt pavement runoff

Wang Xiaoa, Chen Huib,*, Ni Donga and Zhao Jinga

a Research Institute of Highway Ministry of Transport, Beijing 100088, China
b State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100048, China
*Corresponding author. E-mail: chenhui@iwhr.com

ABSTRACT

A hydrodynamic model is developed for rainfall runoff on asphalt pavement using two-dimensional shallow water equations. A simple yet precise expression is presented to compute flow velocity in order to alleviate the problems associated with numerical instabilities due to small water depths of thin sheet flow. The developed model performed well against measured data and numerical results in two segments. Then, the model is applied to study the influence of highway horizontal alignment, drainage manner, rainfall pattern, surface roughness and geometric parameters on pavement runoff. The results demonstrate that: (i) the influence of highway horizontal alignment on pavement runoff is nonsignificant, while that of drainage manner and the pavement surface roughness is significant. Great differences are observed in flow depth under concentrated drainage and overflow drainage conditions, especially in the area beyond 6 m away from the highway center axis; (ii) remarkable differences in maximum flow depth and peak runoff are presented under uneven and even rainfall conditions, while no great differences are found under three uneven rainfall conditions (front type, center front type and back front type); (iii) the sensitivity of the geometric parameters to the maximum flow depth from strong to weak is cross slope, width, slope length, and longitudinal slope under overflow drainage condition; while that is width, slope length, longitudinal slope and cross slope under concentrated drainage condition.

Key words: asphalt pavement, drainage manner, flow velocity, geometric parameters, highway horizontal alignment, rainfall pattern, runoff, two-dimensional shallow water equations

HIGHLIGHTS

- A hydrodynamic model was developed for simulating rainfall runoff on asphalt pavement.
- A new solution of flow velocity was presented for thin sheet flow.
- The influences of highway horizontal alignments, drainage manner, rainfall pattern and geometric parameters on pavement runoff were studied.

INTRODUCTION

The increasing frequency of flooding events on asphalt pavement highlights the importance of studying rainfall runoff, which is associated with traffic safety and the stability of pavement structure. The existing pavement rainfall runoff models can be classified as empirical model, theoretical model and hydrodynamic model. Empirical model is essentially a mathematical expression built by observation or experiment using the regression method. The representative water film thickness prediction models are mainly divided into two types: one allowing for the pavement length, slope and rainfall intensity (Ross & Russam 1968; Anderson 1995), and the other allowing for the pavement length, slope, rainfall intensity and texture depth (Gallaway et al. 1971; Wambold et al. 1983; Ji 2004; Luo et al. 2015). These models are of empirical statistics, and the model parameters are different due to different experiment conditions and methods and lack of clear physical meanings.

The theoretical model is to obtain the mathematical and physical relationship between the variables concerned through theoretical derivation. Zhang & Zhang (2013) applied Xie Cai formula and Manning formula to derive the water film thickness theoretical formula, which separated the cross slope term from longitudinal slope term, and the results demonstrated that the cross slope has a greater impact than the longitudinal slope. Chen (2014) used the continuity and momentum

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY-NC-ND 4.0), which permits copying and redistribution for non-commercial purposes with no derivatives, provided the original work is properly cited (http://creativecommons.org/licenses/by-nc-nd/4.0/).
equations of overland flow to establish the basic differential equation, which mainly took into account the effect of the raindrops, however, neglected the properties of the pavement itself, such as subgrade width and roughness.

The hydrodynamic models are capable of simulating the movement of the pavement runoff through developing a mathematical model of overland flow. Different simplifications of the momentum equation lead to a dynamic wave model (full shallow water equations), a kinematic wave model or a diffusion wave model. Deletic et al. (1996) has studied suspended solids discharge from impervious surfaces during storm events and the kinematic wave was used for overland flow modelling. Cristina & Sansalone (2003) used kinematic wave theory to model rainfall runoff on urban pavement subjected to traffic loadings. Cheah & Ball (2007) used kinematic wave theory for simulating runoff quantity from impervious urban surface. Kazezyilmaz-Alhan & Medina (2007) derived analytical solution for both kinematic and diffusion waves for overland flow and found that the latter is superior the former as it is applicable for problems with variable rainfall intensity. A two-dimensional finite-volume-method (FVM)-based diffusion wave model was developed to simulate the sheet flow at superelevation transition (Jeong & Charbeneau 2010). Cea et al. (2010) compared two-dimensional dynamic wave model with diffusive wave model in simulating rainfall runoff in urban catchment and found that the former is more accurate in numerical results. Gómez et al. (2011) used complete shallow water equations to simulate urban flooding in a street of Barcelona. Staufer et al. (2012) presented an advanced model for calculating water levels on impervious areas and found that the full dynamic wave approximation is necessary under transient boundary conditions. Three approaches (fully dynamic, diffusive and kinematic waves) were applied to simulate overland flow under different rainfall intensities and slopes, numerical results highlighted that significant differences were observed in more complicated topography for which only the fully dynamic model was able to present a good prediction of the observed discharges and water depths (Costabile et al. 2012). Full dynamic wave model was compared with diffusion wave model in the overland flood simulation under a single plane, a cascade of three planes and complicated and irregular topography, the results indicated that full dynamic wave model has better performances in the accuracy and robustness, especially when simulating complex overland flow or the water depth was small (Chen et al. 2017a, 2017b). Therefore, dynamic models were gradually developed to study the characteristics of pavement rainfall runoff (Chen et al. 2017a, 2017b; Geng et al. 2019; Ma et al. 2019).

Building on the existing works, a hydrodynamic model is developed for rainfall runoff on asphalt pavement using two-dimensional shallow water equations, the main contributions of this work are as follows:

1. A water-tongue-velocity-based approach is presented to compute flow velocity in order to alleviate the problems associated with numerical instabilities due to small water depths of thin sheet flow.
2. To demonstrate the applicability of the model, the validation is performed not only with monitored water depths from previous studies, but also with the measured velocities through the field test.
3. The influence factors of pavement runoff are analyzed comprehensively, including highway horizontal alignment, drainage manners, rainfall pattern and geometric parameters.

**METHODS**

**Governing equations**

The pavement runoff is closely related to those geometric parameters such as the pavement width, length, cross slope, longitudinal slope, etc. The horizontal scale is much larger than the vertical, which accords with the assumption of hydrostatic pressure distribution. In addition, the asphalt pavement surface was assumed smooth and impervious. Therefore, the 2D-SWE obtained from the 3D Navier-Stokes equation by depth integration is applied to describe flow on asphalt pavement. The continuity and momentum equations (Li et al. 2016) are as follows:

\[ \frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = q \]  \hspace{1cm} (1)

\[ \frac{\partial (hu)}{\partial t} + \frac{\partial (huu)}{\partial x} + \frac{\partial (huv)}{\partial y} + gh \frac{\partial z}{\partial x} + g \frac{n^2 u \sqrt{u^2 + v^2}}{h^{1.5}} = 0 \]  \hspace{1cm} (2)

\[ \frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hvu)}{\partial y} + gh \frac{\partial z}{\partial y} + g \frac{n^2 v \sqrt{u^2 + v^2}}{h^{1.5}} = 0 \]
where $t$ represents the time; $x$ and $y$ are Cartesian coordinates; $h$ is water depth; $z$ is water level, $z = z_0 + h$; $z_0$ is the bottom elevation; $u$ and $v$ are the depth-averaged velocities in the $x$– and $y$– directions; $g$ is the gravitational acceleration; $n$ is Manning’s roughness coefficient.

**Numerical solution**
The unstructured grid and finite-volume-method (FVM) were applied to perform a discrete solution for 2D-SWE. The control volume was defined by cell-centered scheme, where water depths $h$ and fluxes $Q$ were achieved at the center of the cells and at the midpoints of cell edges, respectively, as sketched in Figure 1, the discretized equations are:

$$h_i^{T+2dt} = h_i^T + \frac{2dt}{A_i} \sum_{j=1}^{m} Q_{ij}L_{ij} + 2dtq_i^{T+dt}$$  \hspace{1em} (3)

$$Q_{ij}^{T+dt} = \text{sign}(z_{j1}^T - z_{j2}^T)h_j^T \frac{1}{n} \left(\frac{|z_{j1}^T - z_{j2}^T|}{d_{lj}}\right)$$  \hspace{1em} (4)

where, $A_i$ is the area of the $i$th control volume; $m$ is the numbers of cell edges; $Q_{ij}$ is the unit-width fluxes at the $j$th edge of the $i$th control volume; $L_{ij}$ is the $j$th edge length of the $i$th control volume; $z_{j1}^T$ and $z_{j2}^T$ are the flow depths of the cells on both sides of the $j$th edge at time $T$; $h_j$ is the average flow depth of the $j$th edge; $d_{lj}$ is the sum length from the centroids of the cells on both sides of the $j$th edge to the midpoint of $j$th edge.

**Water-tongue-velocity-based approach**
Overland flow has the feature of small flow depths and flow velocities are often observed as uneven at the same section where a water tongue appears at some positions with larger velocity, while the velocity is smaller or no water flows through at other positions, as is shown in Figure 2. This behavior of water tongue flow is caused by the absolute roughness of slope surface (Reed 1987; Reed et al. 1994), which is small and can be neglected for deeper flow. However, it would have significant effect on flow depth for thin sheet flow due to an almost same magnitude. Inspired by this phenomenon, a water-tongue-velocity-based approach was presented to describe the relationship between velocity and unit-width fluxes.

It is assumed that cross-section roughness is distributed according to a sine curve, the average roughness can be defined as

$$\overline{h} = \frac{\Delta h}{B} \int_0^B \sin\left(\frac{\pi}{B}x\right) dx = \frac{2}{\pi} \Delta h$$  \hspace{1em} (5)

**Figure 1** | Variable’s notations at considered cell and its neighbors.
where the maximum roughness can be denoted by $\Delta h$; $B$ is the cross-section width. The unit width flux satisfies the continuity equation before and after the appearance of the water tongue, which can be expressed as

$$Qh = Q'(h + \Delta h)$$  \hspace{1cm} (6)

where $q$ is the unit-width fluxes before the appearance of the water tongue; $q'$ is the unit-width fluxes after the appearance of the water tongue. The average velocity after the appearance of the water tongue is determined by

$$v = \frac{Q'}{h + \Delta h}$$  \hspace{1cm} (7)

Substituting the term $q'$ obtained from Equation (6) into Equation (7), we achieve

$$v = \frac{Qh}{(h + \Delta h)(h + \Delta h)}$$  \hspace{1cm} (8)

Substituting the term $\Delta h$ obtained from Equation (5) into Equation (8), we achieve

$$v = \frac{Qh}{\left(h + 2 \Delta h\right)(h + \Delta h)}$$  \hspace{1cm} (9)

here the maximum roughness $\Delta h$ is described by Manning's roughness coefficient $n$, then the average velocity after the appearance of the water tongue can be calculated as

$$v = \frac{Qh}{\left(h + \frac{2}{\pi} n\right)(h + n)}$$  \hspace{1cm} (10)

As can be seen from Equation (10), the velocity is zero at $h$ equals zero and the velocity equals $Q/h$ when the flow depth is greater, which is not only appropriate for the sheet flow, but also for the deeper depth condition. The advantage of this approach over the conventional is that it no longer requires drying and flooding depth and avoids the limitation effectively.

Figure 2 | Phenomenon of water tongue.
MODEL VALIDATION

Segment 1

The model is first validated with the measured rainfall data and observed flow depths of Shenshan Highway from previous studies (Geng et al. 2019). According to the geometric parameters of the monitored segment (shown in Table 1), a hydrodynamic model was developed for rainfall runoff on the observed pavement. 0.5 m*0.75 m rectangle grids are adopted for the model which is discretized into 5,000 grid cells, 10,225 grid edges and 5,256 grid nodes, as shown in Figure 3. The pavement roughness coefficient is taken as 0.013 according to the specifications for drainage design of highway (JTG/T D33-2012) and previous study by Liu & Dong (2020). Figure 4 compares the simulated flow depths with the observed at the observation location (the red point in Figure 3) under an actual rainfall which has a duration of 240 min and a maximum intensity of 5.82 mm/h at 54 min. It is evident in Figure 2 that the temporal evolution of the simulated flow depth agrees well with that of the observed.

Segment 2

The second validation is performed with flow velocities on a segment in the Test Field of RIOH (Research Institute of Highway Ministry of Transport) for Highway and Traffic Engineering, as is shown in Figure 5. Dye tracer method was applied to measure flow velocities at the feature points (black points in Figure 5). This segment is 55 m in length, 2.8 m in width, 0.768% of cross slope and 0.791% of longitudinal slope. Due to the curb, the pavement runoff drains from downstream centrally.

Table 2 lists the simulated flow velocities with the measured at the feature points under a rainfall event of 120 mm/h of rainfall intensity. It is found that both the measured and simulated flow velocities increase along longitudinal distance. The absolute error of each feature point is less than 0.1 m/s, and the maximum relative error is 7.42%, which proves the applicability of the presented model.

Satisfactory agreements with the above two cases demonstrate that the presented model is able to handle the pavement runoff and can describe the runoff characteristics well.

Table 1 | The geometric parameters of segment 1

<table>
<thead>
<tr>
<th>Monitoring location</th>
<th>Cross slope/%</th>
<th>Longitudinal slope/%</th>
<th>Width/m</th>
<th>Drainage manner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near Dongling observation station of Shenshan Highway</td>
<td>2</td>
<td>0.464</td>
<td>18.75</td>
<td>Concentrated drainage (the drainage outlets with space of 20 m and width of 1 m)</td>
</tr>
</tbody>
</table>

Figure 3 | The observation segment grids.
ANALYSIS ON INFLUENCE FACTORS OF PAVEMENT RUNOFF

The influence of highway plane alignments

Two types of highway plane alignment were allowed for in this paper: circular curve and straight line. The straight and circular curve road segment models were established with same cross slope, longitudinal slope, pavement width and slope length, the detailed geometric parameters were shown in Table 3. Rainfall intensity is 100 mm/h and it is assumed that the condition of pavement surface is the same with that in previous chapter, the pavement roughness coefficient is taken as 0.013.
Table 3 | The geometric parameters of the two models

<table>
<thead>
<tr>
<th>Case</th>
<th>Cross slope/%</th>
<th>Longitudinal slope/%</th>
<th>Pavement width/m</th>
<th>Slope length/m</th>
<th>Radius/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Straight segment)</td>
<td>3</td>
<td>1</td>
<td>24</td>
<td>300</td>
<td>–</td>
</tr>
<tr>
<td>2 (Circular curve segment)</td>
<td>3</td>
<td>1</td>
<td>24</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Figure 6 compares the spatial distribution of flow depth between case 1 and case 2. It can be seen that the pavement runoff presents a significant two-dimensional characteristic and the depths of flow keep growing along the cross slope. Figure 7 shows the evolution of flow depth along the outflow section (the y coordinate is equal to 0 m). Little difference is observed in flow depth for these two cases, which demonstrates that the influence of highway horizontal alignment on asphalt pavement runoff is not significant.

![Figure 6](image-url) - The spatial distribution of flow depth for cases 1 and 2.

![Figure 7](image-url) - The evolution of flow depth along the outflow section (y = 0 m).
The influence of roadside drainage manners

There are two drainage manners of pavement runoff: concentrated drainage and overflow drainage. In order to study the differences of runoff characteristics between these two drainage ways, two straight segments were developed with the same geometric parameters (cross slope of 1%, longitudinal slope of 2%, pavement width of 24 m and slope length of 200 m), but with different drainage manners, as is shown in Figure 8 where the curb interval is 20 m and the length of the drainage outlet is 1 m under concentrated drainage condition.

Figure 9 compares the spatial distribution of flow depth under concentrated and overflow drainage conditions. Significant differences are observed in flow field and runoff depth. The ponding depth is up to about 34 mm near the outlet under concentrated drainage condition, while that is only 5 mm under overflow drainage condition.

Figure 10 plots the flow depth variation of downstream outflow section against the vertical distance from the centerline of highway. The flow depth varies as a wide U-shaped or V-shaped curve with similar trend, which shows that the flow depth increases with the vertical distance from the centerline of highway. However, the increasing rates are different and change at the cut-off point 6 m away from the highway centerline. In the area within 6 m away from the highway centerline, the flow...
depth under concentrated drainage condition is roughly identical to that under overflow drainage condition, while in the area beyond 6 m away from the highway centerline, the flow depth under concentrated drainage condition is growing fast and far greater than under overflow drainage condition due to the influence of curbs, which poses a serious threat to driving safety. Thus, we can draw a conclusion that the roadside drainage has a significant effect on asphalt pavement runoff.

The influence of rainfall pattern

Two major types of rainfall were taken in account in this study, one is even rainfall and the other is uneven rainfall which can be further divided into front-type, center front-type and back front-type according to the appearance of maximum rainfall intensity. Therefore, four rainfall events were simulated, front type, center front type, back front type and even type respectively. The total rainfall is 300 mm with a duration of 24 h. The rainfall process of the four rainfall events is depicted in Figure 11. The geometric parameters of simulated segment are the same as that in the previous section and the drainage manner is overland flow.
Figure 12 shows the simulated flow depth and runoff hydrographs under four rainfall conditions. It can be seen from the figure that the maximum flow depth and roadside drainage discharge are significant positive related to rainfall intensity. Both flow depth and roadside drainage discharge are all up to the maximum value of 2.7 mm and 0.016 m$^3$/s respectively at the moment when the rainfall intensity reaches the maximum of 25 mm/h under front, center front and back front rainfall. This suggests that these three rainfall events have no significant effect on the maximum flow depth and peak runoff. Under even rainfall condition, the maximum flow depth and roadside drainage discharge are respectively about 1.8 mm and 0.008 m$^3$/s, which are all less than that under uneven rainfall conditions. Previous studies indicate that the pavement slippery coefficient decreases significantly when flow depth increases from 1 to 5 mm (Zheng et al. 2017). Figure 13 plots the flow depth variation of downstream outflow section against the distance from the centerline of highway. The ponding area where flow depth is greater than 1 mm is obviously wider under uneven rainfall conditions than that under even rainfall conditions. Therefore, uneven rainfall conditions have more remarkable influences on the pavement runoff and driving safety than even rainfall condition.

**Figure 12** | The simulated flow depth and runoff hydrographs under four rainfall events.

**Figure 13** | The variation of flow depth of downstream outflow section.
The influence of pavement roughness

The reference value range of asphalt pavement roughness is 0.013–0.016 according to the specifications for drainage of highways (JTG/T D33-2012). In order to study the influence of pavement roughness, the value was taken with a interval of 0.00025 in the range of 0.013–0.016 and 13 cases were simulated. The geometric parameters of simulated segment are the same as that in the previous section and the drainage manner is overland flow.

Figure 14 depicts the simulated flow depth variation with roughness coefficient. The flow depth is positively correlated with roughness. The flow depth is the smallest of 5.9 mm when the roughness coefficient is 0.013, and that is the largest when the roughness coefficient is 0.016 of 6.5 mm. Thus, the pavement roughness has a significant effect on asphalt pavement runoff.

The influence of geometric parameters

The sensitivity of the geometric parameters was studied with a straight segment, which is the most basic highway alignment. The orthogonal test method was applied and L_9(3^4) orthogonal table was selected to perform the test with four factors and three levels. Four factors are the pavement width, length, cross slope and longitudinal slope. Three levels were determined based on 《Design Specification for Highway Alignment》 (JTG D20-2017) which covers the requirements of highway geometric parameters (Table 4). As proved that drainage manners have significant influences on pavement runoff in the previous section, similarly, the concentrated drainage and overflow drainage were taken into account in the following simulation and sensitivity analysis.

Table 5 lists the design schemes of the orthogonal test and numerical results of maximum flow depth under concentrated and overflow drainage conditions. The minimum and maximum flow depths are respectively 35.1 mm (Case 1) and 52.2 mm (Case 5) under concentrated drainage condition, and that are respectively 5.9 mm (Case 8) and 10.7 mm (Case 3) under overflow drainage condition. Range analysis was further performed on the influence factors of the maximum flow depth and the analysis results were presented in Table 6. The results of range $R_j$ show that the sensitivity of the geometric parameters to the

![Figure 14](image_url) | The variation of flow depth with roughness.

### Table 4 | Values of the orthogonal test factors and levels

<table>
<thead>
<tr>
<th>Level of factor</th>
<th>Cross slope/%</th>
<th>Longitudinal slope/%</th>
<th>width/m</th>
<th>Slope length/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>24</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4</td>
<td>32</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6</td>
<td>40</td>
<td>500</td>
</tr>
</tbody>
</table>
Table 5 | Design schemes of the orthogonal test and numerical results

<table>
<thead>
<tr>
<th>Case</th>
<th>Cross slope/%</th>
<th>Longitudinal slope/%</th>
<th>Width/m</th>
<th>Slope length/m</th>
<th>Maximum flow depth/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>35.1 5.9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>42.1 8.4</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>52.2 10.7</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>44.7 4.9</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>46.9 6.4</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>37.1 5.3</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>50.1 4.7</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>36.6 3.9</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>41.0 5.0</td>
</tr>
</tbody>
</table>

Table 6 | Range analysis results

<table>
<thead>
<tr>
<th>Drainage Manner</th>
<th>Factor</th>
<th>(K_1)</th>
<th>(K_2)</th>
<th>(K_3)</th>
<th>(R_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overflow drainage</td>
<td>Cross slope</td>
<td>25.0</td>
<td>16.6</td>
<td>13.6</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>Longitudinal slope</td>
<td>15.5</td>
<td>18.7</td>
<td>21.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Width</td>
<td>15.1</td>
<td>18.3</td>
<td>21.8</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>Slope length</td>
<td>17.3</td>
<td>18.7</td>
<td>19.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Concentrated drainage</td>
<td>Cross slope</td>
<td>129.4</td>
<td>128.7</td>
<td>127.7</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Longitudinal slope</td>
<td>129.9</td>
<td>125.6</td>
<td>130.3</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Width</td>
<td>108.8</td>
<td>127.8</td>
<td>149.2</td>
<td>40.4</td>
</tr>
<tr>
<td></td>
<td>Slope length</td>
<td>123</td>
<td>129.3</td>
<td>133.5</td>
<td>10.5</td>
</tr>
</tbody>
</table>

maximum flow depth from strong to weak is cross slope, width, slope length, and longitudinal slope under overflow drainage condition, while that is width, slope length, longitudinal slope and cross slope under concentrated drainage condition.

**CONCLUSIONS**

1. A rainfall-runoff model is developed using 2D shallow water equations in their complete form for thin sheet flow on asphalt pavement. This model allows for pavement geometric parameters (pavement width, length, cross slope, longitudinal slope, etc.) and is able to simulate flow movement in temporal and spatial dimension under natural rainfall events. The major advantage of the model is to solve flow velocity by a water-tongue-velocity-based approach, which is not only appropriate for thin sheet flow, but also for the deeper depth condition.

2. To test the model performance, the model was applied to two segments against the observed flow depths and the measured velocities. Satisfactory agreements suggest that the presented model is available to simulate flooding events on asphalt pavement and would be useful for studies on pavement drainage structure optimization, rainfall resource utilization and hydroplaning risk assessment.

3. The influence of highway horizontal alignment on pavement runoff is nonsignificant, while that of drainage manner and the pavement surface roughness is significant. Uneven rainfall conditions have more remarkable influences on the pavement runoff and driving safety than even rainfall condition.

4. The pavement width is the most sensible to flow depth under concentrated drainage condition, increasing longitudinal slope is more beneficial to drain flood waters than cross slope. However, the cross slope is the most sensible to flow depth under overflow drainage condition, increasing cross slope is more conducive to drainage quickly and efficiently.
DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


Gallaway, B. M., Schiller, R. E. & Rose, J. G. 1971 *The Effects of Rain Fall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths*. Texas Transportation Institute, College station.


First received 26 August 2021; accepted in revised form 28 October 2021. Available online 5 November 2021