Analysis of Rainwater Pipelines for Local Flooding Mitigation

Zhaoxiang Zhang¹*, Fan Yang², Yongzhou Huang², Yandong Fu³, Yanjun Li¹, Lei She², Yanyan Zhou², Bin Zhang²

¹ Jiangsu Greenfield Environmental Technology Company Limited, Yixing, Jiangsu Province, 214200, China
² Jiangsu Institute of Urban Planning and Design, Nanjing, Jiangsu Province, 210036, China
³ Xiangtan City Planning and Architectural Design Institute Company Limited, Xiangtan, Hunan Province, 411100, China

*Corresponding author’s e-mail: zhangzhaoxiang1987@hotmail.com

Abstract. PCSWMM was used to perform hydrodynamic simulation. Effect of water level, slope and diameter of rainwater pipelines on local flooding was investigated at free discharge and submerged discharge respectively. Bernoulli equation was applied to theoretical analysis. Results showed that increase of pipe slope and diameter could improve drainage capacity of rainwater pipes at free discharge. Rising water level seriously restricted drainage capacity of rainwater pipes. However, at submerged discharge, pipe slope promoted the construction cost, but it had no effect on its drainage capacity. With the increase of diameter, drainage capacity of rainwater pipes increased. Main factors on drainage capacity of pipes were water head difference between upstream and downstream, pipe diameter and roughness coefficient. Hence, it’s recommended that urban drainage system should properly control water level and increase pipe diameter at submerged discharge. The results are important implications for rainwater pipeline design to prevent local flooding.

1. Introduction

Recently, local flooding disasters caused by heavy rainfall often happen in China [1,2]. Mainly because rainwater cannot be promptly removed from rainwater pipes, the rainwater overflows from inspection wells, or even river flow backward [2,3]. Traditional research on rainwater pipes mostly is focused on their drainage capacity within design recurrence interval, nevertheless a condition in which rainwater pipes encounter storms exceeding design recurrence interval, is ignored sometimes. Overflow of rainwater pipe is an important cause of local flooding disasters. Not only does it influence normal economic and social activities, but it also severely threatens safety of residents’ life and property [2,4,5]. Therefore, it is urgent to determine cause of local flooding in rainwater pipeline quantitatively.

According to hydraulic analysis, design recurrence interval of rainwater pipes means the highest water level of pipes at free discharge rises to the top of pipes encountering a storm with a certain recurrence interval. Surcharge for rainwater pipes refers to the highest water level of pipes exceeding the top of the pipes, but it doesn’t overflow from inspection wells. Flooding signifies rainwater in pipes overflowing from inspection wells, as shown in Figure 1. Usually rainwater pipes are in the state of no pressure flow, when design recurrence interval of the pipes is calculated and studied.
Nevertheless, surcharge and flooding for rainwater pipes are in the state of pressure flow. Recently, local flooding is mainly due to rainwater pipes in the condition of flooding. In engineering practice, it is required that, without local flooding, the smallest investment makes rainwater pipelines service larger catchment areas, possess the more drainage capacity.

Taking rainstorm intensity formula in Nanjing as an example, this paper studied factors affecting drainage of rainwater pipelines with PCSWMM. It provides theoretical support for rational design of rainwater pipelines.

2. Establishment and analysis of the models

2.1 Models establishment

PCSWMM was used to perform hydrodynamic simulation. In models, the total length of rainwater pipelines was 300 m, 2 inspection wells (J1, J2) were set up in the pipe. A water outlet was at the end of the pipe. Runoff of catchment flowed into the inspection well J1, drained through the pipes, as shown in Figure 2.

![Figure 2. Schematic diagram of PCSWMM.](image)

5 groups of PCSWMM for local flooding were performed, as shown in Table 1. In all of the models, the parameters were as follows: infiltration model adopted Green-Ampt model, the width for subcatchments was 200m. The soil was sandy loam, and underlying surface included cement floor and green space. Suction head, conductivity and initial deficit were 50mm, 15mm/h, 0.25, respectively. The Manning roughness coefficient for impervious area and pervious area was 0.1 and 0.024, respectively. Percent of impervious area was 60, and Manning roughness coefficient for all rainwater pipes was 0.013. The design storm was Chicago rainfall model (the rain peak coefficient r is 0.4) in 50 years, deduced by using rainstorm intensity formula in Nanjing. The time step was 1 second in all models.

| Groups number of models | Changing factors | Remarks |
|-------------------------|------------------|---------|
| Group 1                 | Pipe slope       | *Free discharge:* pipe slope is 1‰, 1.5‰, 2‰, 2.5‰, 3‰, 5‰, 10‰, respectively. (pipe diameter is 600mm) |
| Group 2                 | Pipe diameter    | *Free discharge:* pipe diameter is 600mm, 800mm, 1000mm, 1200mm, 1500mm, respectively. |
| Group | Description | Submerged discharge: |
|-------|-------------|---------------------|
| 3     | River water level | the river water level is 0m, 0.6m, 1.0m, 1.25m, 1.5m, 1.8m, respectively. (pipe diameter is 600mm) |
| 4     | Pipe slope   | pipe slope is 1‰, 1.5‰, 2‰, 2.5‰, 3‰, 5‰, 10‰, respectively. (pipe diameter is 600mm) |
| 5     | Pipe diameter | pipe diameter is 600mm, 800mm, 1000mm, 1200mm, 1500mm, respectively. |

Through changing the river water level, pipe slope and pipe diameter, the pipelines were at the critical point of local flooding (the highest water level of pipes was equal to the ground elevation). Then catchment area and maximum drainage flow of the pipelines were studied.

2.2 Results of the models

2.2.1 Free discharge (Group 1 and 2).
In Group 1 models (free discharge, variable pipe slope and invariant pipe diameter), catchment area and maximum flow of pipes increased accordingly. The area and flow were 0.64 ha and 0.41 m³/s while pipe slope was 1‰. They increased to 1.24 ha and 0.72 m³/s with a pipe slope of 10‰, as shown in Figure 3. In the Group 2 models (free discharge), pipe diameter increased from 600mm to 1500mm, catchment area and maximum flow of pipes changed from 0.64 ha and 0.41 m³/s to 14.6 ha and 5.51 m³/s, as shown in Figure 3.

2.2.2 Submerged discharge (Group 3, 4 and 5).
When the river water level rose from 0m to 1.8m, catchment area and maximum flow of pipes declined quickly. For example, they were 0.64 ha and 0.41 m³/s at the river water level 0 m, then decreased to 0.58 ha and 0.37 m³/s at the river water level 0.6 m (the outfall was completely submerged). In extreme cases, the river water level rose to 1.8 m and was equal to the ground level, then catchment area and maximum reduced to 0. It meant pipes completely lost drainage capacity, as shown in Figure 4. In Group 4 models, pipe slope changed with the same water level and pipe diameter at submerged discharge. Catchment area and maximum flow of pipes mainly were invariable for different pipe slope, and were 0.45 ha and 0.3 m³/s roughly (the results weren’t shown). In Group 5 models, pipe diameter increased at submerged discharge, when the river water level was still 1 m. Catchment area and maximum flow of pipes increased quickly. They were 0.45 ha and 0.3 m³/s for pipe diameter of 600 mm, and rose to 9.1 ha and 3.6 m³/s for pipe diameter of 1500mm.

Figure 3. Effect of pipe slope and diameter at free discharge (Group 1 and 2).
Figure 4. Effect of river water level and pipe diameter at submerged discharge (Group 3 and 5).

3. Discussion

PCSWMM includes surface runoff calculation and pipeline network hydraulic calculation [6,7]. The whole calculation process is complex. However, the Bernoulli equation can be used for the simple hydraulic calculation of rainwater pipelines [8,9].

\[ Z = h_w - \Delta h = 10.3 \cdot \frac{n^2}{D^{5/3}} \cdot Q^2 \cdot L \]  

Where \( Z \) (m) is water head of rainwater pipelines, \( h_w \) (m) is hydraulic loss of rainwater pipelines, \( \Delta h \) (m) is linear hydraulic loss of rainwater pipelines, \( n \) is Manning's roughness coefficient, \( D \) (m) is pipeline diameter, \( Q \) (m\(^3\)/s) is volumetric flow rate of rainwater pipe, and \( L \) (m) is the length of pipelines.

In general, the local head loss relative to linear hydraulic loss of rainwater pipelines is very small. Linear hydraulic loss of rainwater pipelines (\( \Delta h \)) approximates hydraulic loss of rainwater pipelines (\( h_w \)).

According to Equation (1), increase of pipe slope leads to greater water head of pipes (\( Z \)), at free discharge. Therefore, the greater water head (\( Z \)) promotes rise of maximum flow and catchment area. Larger pipe diameter decreases linear hydraulic loss, boosts maximum flow and catchment area.

It can be derived that flow of pipes is related to pipe diameter, Manning's roughness coefficient and water head, and it has no relation to pipe slope at submerged discharge. At submerged discharge, the lower river water level is, the more water head (\( Z \)) is, and the more flow and catchment area are. When water head (\( Z \)) was invariable, such as Group 4 models, change of pipe slope made little difference to the length of pipes, and hydraulic loss of pipes stayed almost unchanged. Maximum flow and catchment area of pipes had almost no change accordingly. In addition, with invariable water head (\( Z \)), such as the Group 5 models, increase of pipe diameter diminished hydraulic loss of pipes and promoted maximum flow and catchment area. It was reported that node flooding and pipe hydraulic load could be alleviated by increasing the pipe diameter [10]. In addition, rainwater storage could reduce peak outflows and mitigate local flooding [11,12,13].

Many factors affect local flooding, including river level, underlying surfaces, LID (Low Impact Development), sponge city, maintenance of rainwater pipe, ground elevation and so on [14,15,16,17]. When it is difficult to ensure free discharge of outlet, such as high water level or rapid rise of water level encountering storms. In order to enhance ability of local flooding prevention, diameter of rainwater pipelines should be increased to meet design recurrence interval, and increase of pipe slope should be avoided. In theory, the pipe slope equal to zero is the most economical at submerged discharge, but in order to facilitate maintenance of pipelines and to avoid pipeline blockage, it is suggested that rainwater pipelines should meet minimum design slope of related code.
4. Conclusion
By simulating effects of slope, pipe diameter and water level on local flooding, main factors were studied theoretically. At free discharge, slope and diameter could improve drainage capacity of rainwater pipes. Rising water level seriously restricted drainage capacity of rainwater pipelines, therefore water level should be reasonably controlled at prevention of local flooding. Increase of pipe slope at submerged discharge not only led to increase of construction cost, but also basically failed to improve drainage capacity of pipes. Although increase of pipe diameter led to increase of construction cost, it can effectively improve drainage capacity of pipes. Therefore, when submerged discharge may occur, increasing pipe diameter to meet design recurrence interval for pipes should be adopted.

References
[1] Lin T., Liu, X.F, Song J.C, Zhang G.Q, Jia Y.Q., Tu Z.Z., Zheng Z.Z., Liu C.L. (2018) Urban waterlogging risk assessment based on internet open data: A case study in China, Habitat International, 71: 88-96.
[2] Mignot E., Li X.F, Dewals B. (2019) Experimental modelling of urban flooding: A review, Journal of Hydrology, 568: 334-342.
[3] Zeng S.Y, Guo H., Dong X. (2019) Understanding the synergistic effect between LID facility and drainage network: With a comprehensive perspective. Journal of Environmental Management, 246: 849-859.
[4] Paquier A., Mignot E., Bazin. P.H. (2015) From Hydraulic Modelling to Urban Flood Risk. Procedia Engineering, 115: 37-44.
[5] Fang Q.H. (2016) Adapting Chinese cities to climate change. Science, 354: 425-426.
[6] Hamouz V., Muthanna T.M. (2019) Hydrological modelling of green and grey roofs in cold climate with the SWMM model. Journal of Environmental Management, 249: 1-18.
[7] Paule-Mercado M.A., Lee B.Y., Memon S.A., Umer S.R., Salim I., Lee C.H. (2017) Influence of land development on stormwater runoff from a mixed land use and land cover catchment. Science of The Total Environment, 599-600: 2142-2155.
[8] Baldesi L., Maccari L., Cigno R.L. (2020) Infective flooding in low-duty-cycle networks, properties and bounds. Computer Communications, 151: 216-226.
[9] Willi H.H., Oscar C.O., Kolumban H. (2019) Correspondence between de Saint-Venant and Boussinesq: 1: Birth of the Shallow–Water Equations. Comptes Rendus Mécanique, 347: 632-662.
[10] Xie J.Q., Chen H., Liao Z.L., Gu X.Y., Zhu D.J., Zhang J. (2017) An integrated assessment of urban flooding mitigation strategies for robust decision making. Environmental Modelling & Software, 95: 143-155.
[11] Liang R.J., Matteo M.D., Maier H.R., Thyer M.A. (2019) Real-Time, Smart Rainwater Storage Systems: Potential Solution to Mitigate Urban Flooding. Water, 11: 1-23.
[12] Matteo M.D., Liang R., Maier H. R., Thyer M. A., Simpson A.R., Dandy G.C., Ernst B. (2019) Controlling rainwater storage as a system: An opportunity to reduce urban flood peaks for rare, long duration storms. Environmental Modelling & Software, 111: 34-41.
[13] Deitch M.J., Feirer S.T. (2019) Cumulative impacts of residential rainwater harvesting on stormwater discharge through a peri-urban drainage network. Journal of Environmental Management, 243: 127-136.
[14] Wang G.F., Chen, J.C., Zhao C.H., Zhou, X.X., Deng X.Z. (2017) Exploration of the causality between area changes of green spaces and waterlogging frequency in Beijing. Physics and Chemistry of the Earth, Parts A/B/C, 101: 172-177.
[15] Jiao S., Zhang X.L., Xu Y. (2017) A review of Chinese land suitability assessment from the rainfall-waterlogging perspective: Evidence from the Su Yu Yuan area. Journal of Cleaner Production, 144: 100-106.
[16] Hu M.C., Zhang X.Q., Li Y., Yang H., Tanaka K. (2019) Flood mitigation performance of low impact development technologies under different storms for retrofitting an urbanized area. Journal of Cleaner Production, 222: 373-380.

[17] Huang H.B., Chen X., Zhu Z.Q., Xie Y.H., Liu L., Wang X.W., Wang X.N., Liu K. (2018) The changing pattern of urban flooding in Guangzhou, China. Science of The Total Environment, 622-623: 394-401.