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Experimental Study on Validation of Combined Model for Urban Inundation Analysis

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Synopsis

Recently, scientists have developed many numerical models to predict of urban inundation damage due to climate change and heavy rainfall by using the combined sewer system. The sewer system is one of the most important factors in urban flood inundation models, and the inlet discharge through storm drains is also very important input data in a sewer system.

Hence in this study, we employ physical experiments to validate the numerical model of stormwater interaction, not only between the ground surface and the sewer system, but also the drain channel in order to estimate the application of suggested coefficients (Lee et al., 2012). This experimental setup consists of a rainfall supplier, a surface flood plain with buildings, a sewer pipe, and connection pipes (drain channels) between the ground and sewer pipes. From the comparison between experimental results, simulation piezometric heads, and discharge of the sewer pipe, the above mentioned discharge coefficients and application of the model are validated.

Consequently, in the steady-state cases, the weir and orifice formulas with new coefficients could reproduce the experimental results very well. In the unsteady-state cases, increasing timing of surcharge and maximum inundation depth could reproduce the experimental results very well, but decreasing timing was overestimated.

Keywords: urban inundation, sewer system, drain channel, discharge coefficient

1. Introduction

Urban inundation due to climate change and heavy rainfall is a serious problem for many cities worldwide. Therefore, it is important to accurately simulate urban hydrological processes and efficiently to predict the potential risks of urban floods for the improvement of drainage designs and implementation of emergency actions (Li et al., 2009). In order to solve these kinds of problems, numerical simulation models of flood inundation in urban environments with two-dimensional models have become more popular in the last few years (Cea et al., 2010), and surface flood modeling in urban environments is a challenging task for a number of reasons: the presence of a large number of obstacles of varying shapes and length scales, building storage, complex geometry of cities, etc. (Mignot et al., 2006).

The urban environment is highly heterogeneous in terms of land use, drainage systems, and other factors that influence the processes of the water cycle, including rainfall, surface runoff, infiltration and movement of water in the sub-soils, interaction between surface water and groundwater, interaction between the drainage network and groundwater, and evapotranspiration (Campana and Tucci, 2001). In addition to these complex interactions, there is a well-recognized lack of experimental data to validate and to compare the performance of flood inundation models, as studies of urban flooding are devoted to model sensitivity analysis (Hunter et al., 2007).

The sewer system is one of the most important factors in urban flood inundation models and the inlet discharge through the storm drains is also very important data as an input data of sewer system. However, it is very difficult to estimate how much of discharge on the ground surface is drained through storm drains. Also, discharge coefficient of each formula is different depending on research groups.

Kawaike et al. (2011) carried out experimental study on validation of stormwater interaction model using step-down formula and overflow formula but suggested coefficients couldn't reproduce very good agreement under the unsteady-state condition. Hence, in this study, fundamental laboratory-scale experiments to validate applications of the new weir and orifice coefficients (Lee et al., 2012) for urban inundation modeling are carried out using the same experimental setup as Kawaike et al. (2011), and the sub-model of interaction between the drainage channel and sewer pipe, as well as between the drainage channel and sewer pipe, is validated by comparing the experimental data and simulation results.

2. Experimental setup

2.1 Laboratory-scale experimental setup

Fig. 1 and Fig. 2 show the experimental setup, which consists of four parts: rainfall supplier, ground surface part, drainage channel part, and sewer pipe system. The experimental scale is assumed to be 1/20, and Table 1 shows the ratios between the real and experimental scale based on Froude's similarity law.

Fig. 1 Experimental setup

The rainfall supplier is the equipment that supplies rainfall to the ground surface from 20 nozzles, and it is located 3.5m above the ground to spread water efficiently. The open space between the rainfall supplier and the ground surface is surrounded by a vinyl curtain in order to prevent the

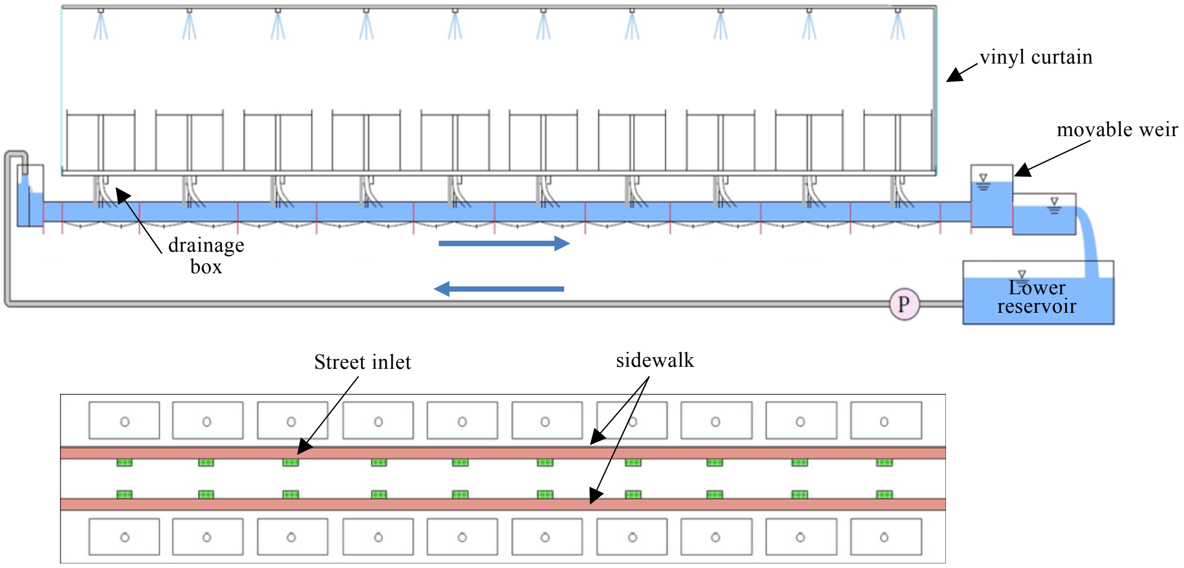


Fig. 2 Side view and plan view of experimental setup

spread rainwater from falling down outside of the ground surface, so that all the rainwater is supplied to the ground surface. The maximum rainfall intensity is 28.49mm/h, and according to Table 1, experimental rainfall is approximately equivalent to rainfall of 127mm/h in a real scale.

The ground surface part has an acrylic flat inundation basin that is 10m long and 2m wide, on which there is a roadway of 0.5m sidewalk of 0.15m, and 10 buildings on both sides, as shown in Fig. 2.

Table 1 Ratio between real scale and experimental scale

Index	Ratio
Length	1/20
Velocity	1/4.47
Discharge	1/1,790
Roughness coefficient	1/1.65

There are 20 side gutters on the ground surface and drain box, which has a width of 5cm and a height of 5cm. It is attached below each side gutter and also each drain box is connected through the small square pipe, which has 2.5cm width and 1.5cm height. The elevation difference between the drain box and connection pipe is 1.5cm, as shown in Fig. 3.

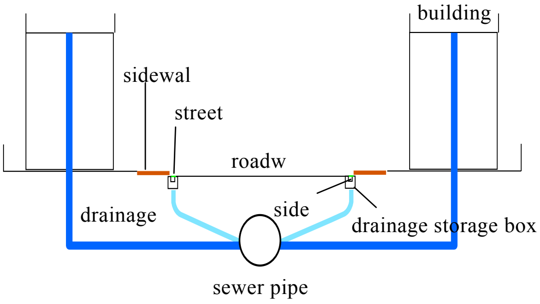


Fig. 3 Cross section of the experimental

One circular pipe with a diameter of 5cm and 1/714 slope is installed beneath the inundation basin. Fig. 3 shows the cross section of the experimental setup. Stormwater dropped on the building roof is drained into the sewer pipe through the small drainage tube from the holes at the center of the roof, while stormwater dropped on the ground surface falls down in the drainage box through the street inlet on both sides of the roadway; in turn, that water drains from the bottom of the drainage box into the sewer pipe through the drainage tube. When the piezometric head of the sewer pipe rises, stormwater would surcharge from the sewer pipe into the drainage box, and if that drainage box is also surcharged, inundation can occur from the drainage box to the ground surface reversely. The water level of the downstream reservoir is adjustable using the movable rectangle weir, and total discharge can be calculated by the v-shape weir, which is located at one end of the equipment. Stormwater stored in the downstream storage reservoir is pumped to the upstream end and added as the input discharge from the upstream end of the sewer pipe.

From the above descriptions, three factors determine the experimental conditions in this experimental setup: rainfall intensity, upstream input discharge, and downstream water level.

2.2 Model conceptualization

Fig. 4 shows a schematic of the rainfall-runoff process, as represented in this study. The models used here are composed of two analytical models: a hydrological model that can simulate direct runoff from rainfall, and a hydraulic model that can simulate drainage channel and sewer system flow. The maximum rainfall value is directly used as an effective rainfall value. The drainage channel between the surface and the sewer system is assumed to be a one-dimensional flow and is the point of flow exchange between them.

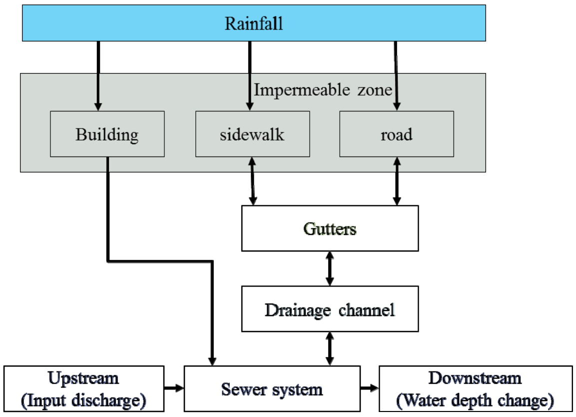


Fig. 4 Schematic of the rainfall-runoff process

3. Numerical simulation

3.1 The governing equation and numerical scheme

The numerical simulation model used here is the third author's conventional model (Kawaike et al., 2011), which consists of horizontal 2D inundation flow model, 1D slot model of drainage channel flow, and 1D slot model of sewer pipe flow (Chaudhry, 1979); the model estimates interaction flow discharge not only between the ground surface and drainage channel, but also between the drainage channel and the sewerage system, using the orifice and weir formula, which apply new coefficients (Lee et al., 2012).

3.1.1 2D inundation flow model

The governing equations used for 2D inundation flow model are as follows.

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=r_e-q_{drain} \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{gn^2M\sqrt{u^2+v^2}}{h^{4/3}} \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{gn^2N\sqrt{u^2+v^2}}{h^{4/3}} \tag{3}$$

where h is water depth; H is water level; u, v are x, y directional velocity; M (=uh); N (=vh) is x, y directional flow flux; r_e is effective rainfall; q_{drain} is drainage discharge from the ground surface to the drainage box per unit area (if its value is negative, that means surcharge flow discharge); g is gravity acceleration; and n is Manning's roughness coefficient. Computational meshes are rectangular in shape (Δx=5cm, Δy=5cm). The numerical analysis technique used for the surface flow and drainage channel, as well as for sewerage system flow, is the unsteady flow equation by the explicit finite difference method (FDM) employed with the leap-frog calculation method.

3.1.2 Drainage channel model

A 1D flow simulation with a slot model is conducted to simulate the flow within a drainage channel. The governing equations are as follows.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q' \tag{4}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (uQ)}{\partial x}=-gA\frac{\partial H_d}{\partial x}-\frac{gn^2|Q|Q}{R^{4/3}A} \tag{5}$$

where A is the wet area of the cross section, Q is flow discharge, q' is inflow and outflow discharge in drainage box per unit area, u is velocity, R is hydraulic radius, and n is the roughness coefficient (n=0.012, adopted for the drainage channel in this study). H_d is piezometric head (H_d=z_d+h), z_d is bottom elevation of the drainage channel, and h is water depth, determined as follows.

$$h=\begin{cases} A/w_d & : A\le A_d \\ h_h+(A-A_d)/B_{sd} & : A>A_d \end{cases} \tag{6}$$

where w_d is width of drain channel, h_h is height of drainage channel, A_d is cross sectional area of drainage channel, and B_{sd} is slot width of drainage channel, determined as follows.

$$B_s=\frac{gA_d}{a_d^{\,2}} \tag{7}$$

a_d is a pressure wave speed for drainage channel, and 1.7m/s is used in this study.

3.1.3 Sewerage model

The 1D flow simulation with a slot model is conducted to simulate the flow within a sewer pipe. The governing equations are as follows.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{8}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (uQ)}{\partial x}=-gA\frac{\partial H_p}{\partial x}-\frac{gn^2|Q|Q}{R^{4/3}A} \tag{9}$$

where A is the wet area of the cross section, Q is flow discharge, q is lateral inflow discharge per unit pipe length (from the drainage channels and buildings), u is velocity, R is hydraulic radius, and n is roughness coefficient (n=0.012, as adopted for the sewer pipe in this study). H_p is piezometric head (H_p=z_p+h), z_p is bottom elevation of the sewer pipe, and h is water depth determined as follows.

$$h = \begin{cases} f(A) & : A \leq A_p \\ D + \left(A - A_p\right)/B_s & : A > A_p \end{cases} \tag{10}$$

where f is the function of the relationship between water depth and the wet area of the cross section of a circular pipe, A_p is the cross sectional area of the pipe, D is the pipe diameter, and B_s is slot width, determined as follows.

$$B_s = \frac{gA_p}{{a_s}^2} \tag{11}$$

a_s is a pressure wave speed for a sewer pipe, and 3.8*m/s* is used in this study.

4. Interaction model

4.1.1 Interaction model between ground surface and drain channel

Stormwater on the ground surface computational mesh with street inlet is drained in the drainage channel through the street inlet. That drainage discharge is estimated by the weir and orifice formula.

Weir formula :

$$Q = \frac{2}{3} C_{dw} l \sqrt{2g} (h_m - h_d)^{3/2} : (h_m - h_d) \leq B_0 / 2 \tag{12}$$

Orifice formula :

$$Q = C_{do} A \sqrt{2g(h_m - h_d)} \quad : (h_m - h_d) > B_0 / 2 \tag{13}$$

where Q is drainage discharge from the ground surface into the drainage channel, h_m is water depth on the ground surface, and h_d is the difference between the piezometric head of the drainage channel and ground elevation; however if the piezometric head of the drainage channel more smaller than ground elevation, h_d should be zero. C_{dw} and C_{do} are the coefficients of the weir and orifice formula, respectively, and the values of 0.48 and 0.57 are used in this study, respectively. B_0 is the smallest width of the street inlet, and L is the perimeter length of the street inlet. Stormwater is supposed to be immediately drained into the drainage channel.

On the contrary, when the piezometric head exceeds the water level on the ground surface, stormwater surcharge begins to occur from the street inlet. Surcharge flow discharge is estimated by the following overflow formula.

$$Q = -\frac{2}{3} C_{dw} l \sqrt{2g} (h_d - h_m)^{3/2} \quad : (h_d - h_m) \leq B_0 / 2 \tag{14}$$

$$Q = -C_{do} A \sqrt{2g(h_d - h_m)} \quad : (h_d - h_m) > B_0 / 2 \tag{15}$$

The negative sign on the right side denotes surcharge flow onto the ground surface.

q_{drain} in Eq.(1), q' Eq(4), and q in Eq(8) are as follows, respectively.

$$q_{drain} = Q / S_g \tag{16}$$

$$q' = Q / \Delta x_d \tag{17}$$

$$q = Q / \Delta x_s \tag{18}$$

where S_g is the computational mesh area on the ground surface, x_d is the discretized length of one segment of drainage box, and x_s is the discretized length of one segment of sewer pipe.

4.1.2 Drainage through drainage box and building roof

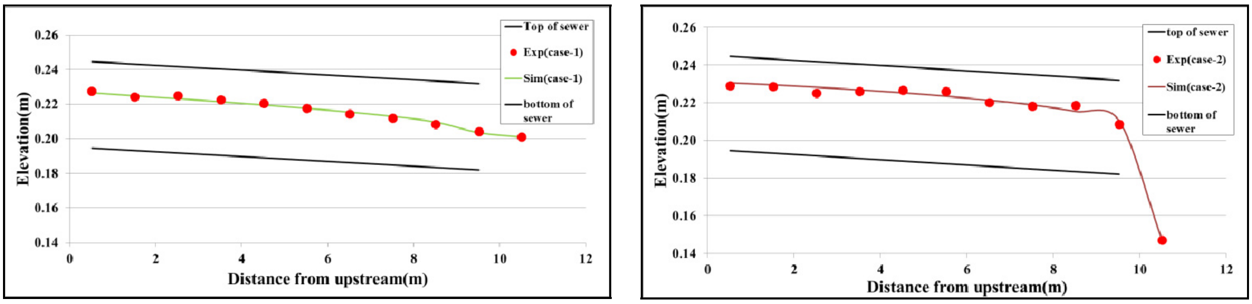
Stormwater dropped on the drainage box, roof of building, and ground surface is separately treated (Kawaike et al., 2011). In this study, the computational mesh size is very small for the drainage box and the roof of building area, and stormwater is drained according to Eqs. (12) ~ (15). Stormwater on the drainage box and the roof of building is immediately drained into the sewer pipe.

5. Validation of numerical interaction model

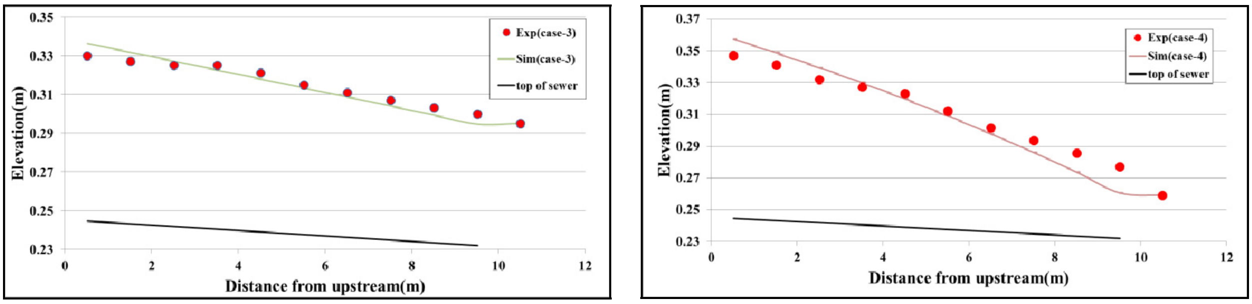
In this study, steady-state and unsteady-state experiments were conducted. In the steady-state cases, the slot model was validated with the water surface profile and piezometric head of the sewer pipe under simple hydraulic conditions. In the unsteady-state case, application of the interaction model using the weir and orifice formula, applying new coefficients, is validated with drainage and surcharge discharge.

Table 2 Experimental conditions of steady state cases

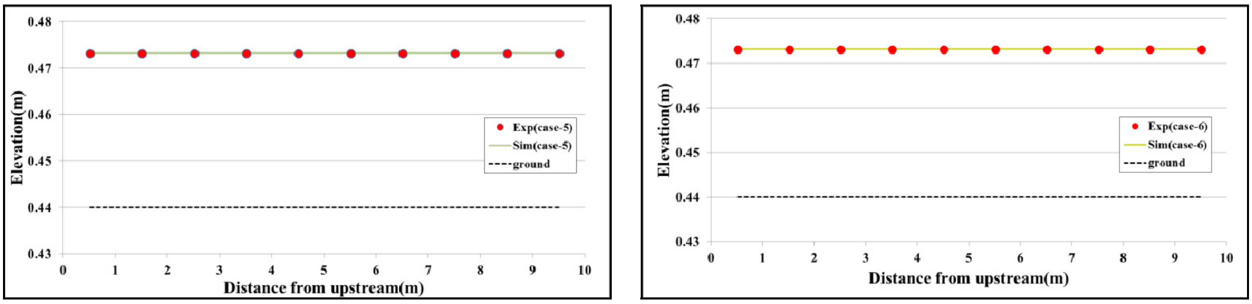
	Upstream input discharge (l/s)	Downstream water level(m)	Rainfall intensity (mm/h)	Flow state within the pipe
1	0.260	0.201	0.0	Open channel flow
2	0.206	0.147	28.49	
3	0.629	0.295	0.0	Pressurized flow
4	0.779	0.259	28.49	
5	1.360	0.405	0.0	Pressurized flow with overland inundation
6	1.145	0.205	28.49	



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4

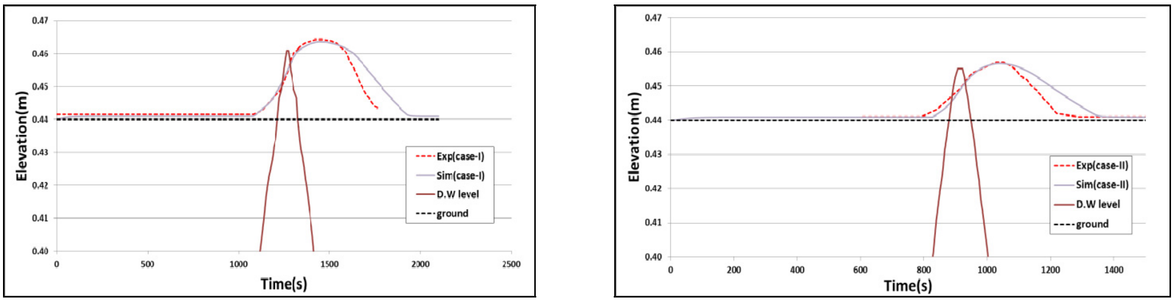


(e) Case 5 (f) Case 6

Figure. 5 Comparison between experiments and simulation results of steady-state condition

5.1 Steady-state experiments

Three factors (rainfall intensity, upstream inflow discharge and downstream water level) of the experimental setup are combined, as shown in Table 2, and those six steady-state experiments were carried out. These six cases can be divided into three categories of flow state within the sewer pipe that is open channel flow, pressurized flow,



(a) Case I (b) Case II

Fig. 6 Comparison between experiment and simulation results on unsteady-state cases

and pressurized flow with overland inundation. In the experiments, water surface on the ground is recorded using video cameras, and depending on the flow state within the sewer pipe, the following are measured;

- Open channel flow: water level within the sewer pipe
- Pressurized flow: water level within the drainage tube connected to the drainage box
- Pressurized flow with overland inundation: water level on the ground surface

Fig. 5 shows the comparison between the experimental and simulation results of the representative model. . In all cases, the simulation results are close to the experimental results, even if the simulation results at the upstream parts were slightly overestimated and underestimated at the downstream parts in the pressurized flow cases. From those results, in steady-state cases, the slot model and interaction model, as well as new coefficients used in this study were validated to reproduce the water surface profile and piezometric head of the sewer pipe.

5.2 Unsteady-state experiments

In the unsteady-state experiments, the inundation process of surcharge flow, overland inundation, and drainage flow are made to happen by gradual ascent and descent of the downstream water level. Two cases of experiments were carried out, and Table 3 shows the experimental conditions. In Case I and Case II, water level on the ground surface at upstream is measured. Video cameras are used to record change of inundation depth at the upstream and water level at the downstream.

Table 3 Experimental conditions of unsteady state cases

	Upstream input discharge (l/s)	Downstream water level change
I	1.239	Slowly change
II	1.239	Quickly change

Fig. 6 shows the comparison between experimental results and simulation results of Case I and II. According to simulation results, increasing time of inundation on the ground shows the correct results without delay. In addition, maximum inundation depths show reasonable results.

However, in both cases, simulation results of water level on the ground surface decrease more slowly than experimental data.

6. Conclusions

In this study, in order to validate the stormwater interaction model not only between the ground surface and drainage channel, but also between the drainage channel and sewerage system, experiments were carried out and validation data were obtained and compared with simulation results.

Consequently, in the steady-state cases, the weir and orifice formula with new coefficients could reproduce the experimental results very well. However, the piezometric head at upstream part slightly overestimated and that trend was represented according to increasing input discharge. On the other hand, opposite trend is observed at the downstream. It is judged that the head losses between the tank and sewer pipe were not considered in this model.

In the unsteady-state cases, increasing timing of surcharge and maximum inundation depth could reproduce the experimental results very well, but decreasing timing was overestimated. Also unfortunately, the experimental piezometric head in pipe was not measured because of severe piezometric movement caused by interaction.

Therefore, in the next study, experimental equipment improvement is supposed to improve in order to measure stable piezometric head in the pipe and more concentrated research which can analyze the reason of decreasing time disagreement should be carried out in order to solve this problem.

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都市洪水氾濫解析のための統合モデルの開発に関する実験的研究

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要　旨

最近では, 気候変動や集中豪雨による都市浸水被害を予測するために, 多くの研究者たちが地下 - 地上の接続モデルを使用している。下水管システムは, 都市浸水モデルの中で最も重要な要素の一つであり, storm drain を介して流入される流量は, 下水管システムの入力データとしては非常に重要である。しかし, storm drain を介して流入される流量を測定することは非常に困難であり, 多くの研究者たちもモデルを検証するためのパラメータとしてそれぞれ別の流量係数を示している。したがって, 本研究では, 実際の実験によって提案された流量係数（Lee et al., 2012）の適用性を判断するために, 検証実験とデータの取得, モデル化を行った。本実験装置は, 降雨装置, 地上の氾濫範囲, 下水管および地上部の下水管を接続する小さな水路（drain channel）で構成されています。実験結果とモデルの結果の比較分析を行い, 先述の流量係数の適用性を検証した。その結果, ジョンサンリュ条件では, 新しい係数が適用されたダム, オリフィス式が実験結果をよく再現した。非上流の条件では, 地上部の氾濫時や最大浸水植えよく予測されたが氾濫流量の排水時に若干の遅延が観測された。

キーワード: 都市洪水, 下水管システム, 流量係数