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Experimental Study on Head Losses in the Sewer Pipe due to Manhole Shapes

Seungsoo LEE(1), Hajime NAKAGAWA, Kenji KAWAIKE and Hao ZHANG

(1) Graduate Student, Department of Civil and Earth Resources Engineering, Kyoto University

Synopsis

Rapid urbanization has caused complicated sewerage system as well as landscape of building structures. Since the major loss in the pipe is friction, it is possible to neglect energy losses while designing sewer systems with free surface flow, but under the pressurized condition, the energy losses may exceed the friction losses and reduce system capacity significantly, thus it is needed to consider the energy losses.

Basically one-dimensional model is used to simulate sewerage system involving manholes and junctions with pipe configuration for calculating time and capacity efficiency although the head losses caused by manhole and pipe configuration are not one-dimensional (1D) phenomena. It causes problems that non 1D phenomena are artificially treated as one-dimensional.

Therefore it is necessary to develop the model which can reflect the head losses depending on the pipe configuration and manhole shapes. In order to develop the simulation model, the fundamental laboratory experiments were conducted to estimate the effects of head loss depending on different manhole shapes with no benching and no invert. First, straight case experiments were conducted to evaluate the head loss for circular and square type manhole shape under the unsteady-state as well as steady-state condition and then numerical simulation model was developed and validated to confirm an applicability of the model using head loss coefficients obtained from laboratory experiments.

Keywords: urban inundation, sewerage system, manhole head loss, sewer network model

1. Introduction

Rapid urbanization caused various social problems. With increasing urbanization and increasing drainage and water quality requirements, sanitary sewer and storm water systems have been drastically complicating. The hydraulic characteristic of a drainage system often reveals many complex phenomena, such as back water effects from outlet boundary or hydraulic structures, confluence interactions at manholes, interchanges between pressurized pressure flow and free surface flow conditions, and may cause serious problems, such as inundation caused by lack of sewer pipe capacity, blown-off manhole covers and sewer pipe rupture and soil erosion (Zhao et al., 2006). Normally sewer systems are designed to carry free-surface flow where the energy losses are neglected for simplicity. The friction head losses are major losses in pipes, and it can be predicted with a relatively accuracy using the Darcy-Weisbach equation (Johnston and Volker,

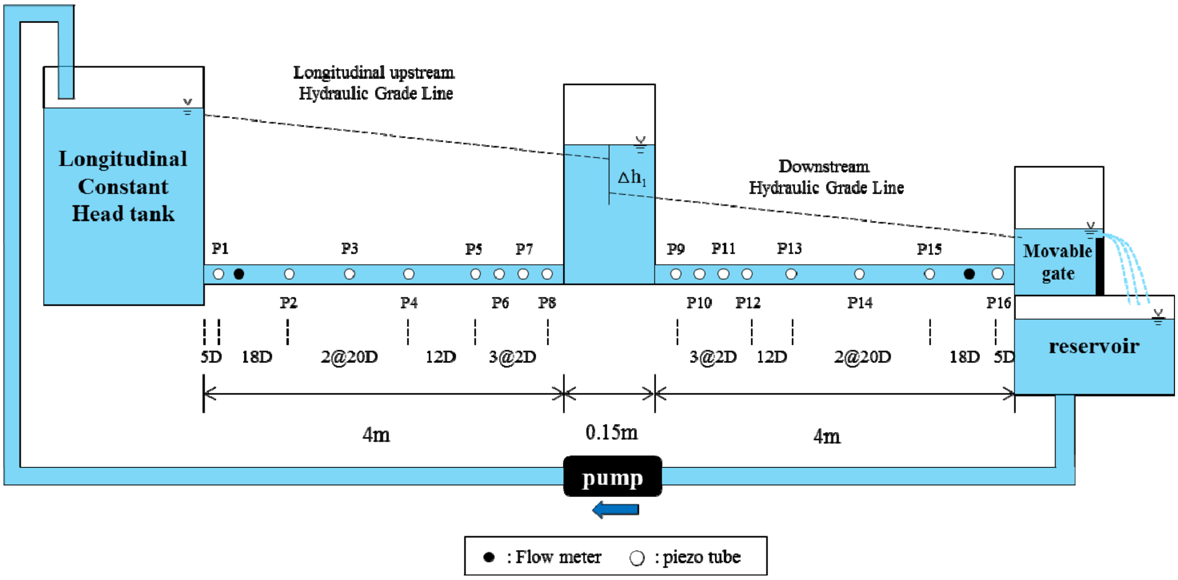


Fig. 1 Side view of experimental facility

1990). However the minor losses caused by junctions, sewer inlets, house connections, and other appurtenances in many pressurized sewer systems, exceed the friction losses and reduce system capacity significantly (Marsalek, 1984). Recently, pressurized flow is occurring more frequently in sewer systems due to a growth of urbanization, increased impermeable layer, complex sewer pipes configuration and increased rainfall frequency due to climate change. Although the hydraulic characteristics of sewer flow in a single pipe are understood reasonably well, limited research has been carried out on sewer junctions depending on pipe configurations or adjoining angle.

The determination of pressure changes across the junction box requires the determination of the vertical distance between the inlet and outlet hydraulic grade lines (HGLs) at the manhole as shown in Fig.1 (Sangster et al., 1958). Defined head loss coefficients to be

$$K_1 = \frac{\Delta h_1}{v^2/2g} \tag{1}$$

where K_1 is the head loss coefficient, Δh_1 is a pressure head change in pipe, g is the acceleration due to gravity and v is a mean velocity in the outlet pipe. Sangster et al. (1958) suggested empirical relationships to decide not only the head loss coefficient of two pipe case, but also three pipes case coefficients. After that, many similar researches were carried out to improve and modify a measurement technique according to various circumstances near the manholes.

Marsalek (1984) measured the effect of different type of manhole benching as well as the manhole head losses for a system with a 90° bend or a “T” junction. A submerged jet theory for the flow in straight through manholes was presented by Pedersen and Mark (1990) to determine the head losses in manholes. Wang et al. (1998) conducted laboratory experiments to determine the head loss coefficients with regarding to various pipe configurations and flow rates. Merlein (2000) developed the mathematical model using Predictor-Corrector method which could calculate water depth change under unsteady-state condition but that model can calculate only the water depth of manhole since it was assumed that manholes hydraulically behave like surge tanks. Supercritical flow at sewer junction in 45° junction manhole was studied by Del Giudice and Hager (2001) and 90° junction was investigated by Gisonni and Hager (2002). Zhao et al. (2004) carried out a model study for a 25.8° combining junction with two inflows and one outflow. Zhao et al. (2006) conducted experiments to improve understanding on flow regimes in sewer junctions.

Head losses at sewer junctions are affected by flow rate, junction geometry, adjoining angle and the change in pipe diameter between the inflow and outflow lines. To better understand these complicated hydraulic features and accurately simulate flows in a complicated sewerage system, unsteady-state flow model based on the solution of the full hydrodynamic equations is needed to consider the head loss phenomena.

Therefore in this study, fundamental laboratory experiments to estimate the head losses are carried out with no benching and no invert. First of all, straight cases are conducted in order to evaluate the head losses depending on manhole shape between circular and square type and then, numerical simulation model is developed and tested to confirm applicability based on experimental data from laboratory experiments.

2. Description of experimental setup

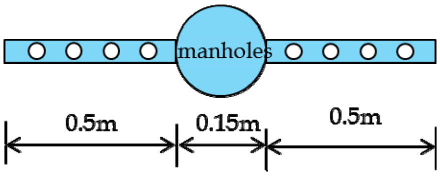
The experiments were carried out in a flume located at the Ujigawa Open Laboratory (UOL) of Disaster Prevention Research Institute (DPRI). Fig. 1 also shows a side view of experimental facility. The experimental setup is designed to estimate head losses between manhole and pipes regarding to different manhole shapes. There is an upstream input discharge tank (longitudinal constant head tank) of 0.3m×0.5m×1.0m and a downstream water tank of 0.3m×0.5m×1.5m with movable gate to adjust downstream water level. Each tank is connected to manhole by the transparent acrylic pipes of 4.0m long and 0.05m diameter with zero slopes. Two flow meters were installed in which the first meter is just in front of the upstream head tank and the second one is just before the downstream outlet tank as shown in Fig. 1.

The input discharge can be supplied to the upstream tank through the circulation pump. The pump can be accurately controlled by the RPM controller. Totally sixteen piezometer tubes are used to read the water head at a bottom of pipe. Out of that, four of them were set at intervals of 1.0m, and the rest four are set at intervals of 0.1m to read a water head carefully near the manhole per pipe as shown in Fig. 1. In addition, the water levels of the

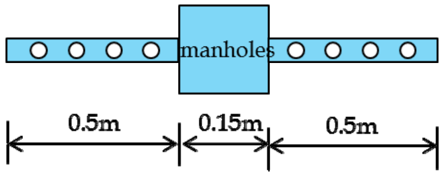
Table 1 Steady case of 2 pipes

Number	Upstream discharge(l/s)	Mean Velocity(m/s)	Froude Number	Downstream water level(m)
C-S*-1	3.03	1.54	2.20	0.026
C-S-2	2.71	1.38	1.97	0.026
C-S-3	2.42	1.23	1.76	0.026
C-S-4	2.11	1.07	1.53	0.028
C-S-5	1.80	0.92	1.31	0.028
C-S-6	1.51	0.77	1.10	0.026
C-S-7	1.29	0.66	0.94	0.024
C-S-8	0.91	0.46	0.66	0.019
C-S-9	0.87	0.29	0.41	0.013
S-S*-1	3.04	1.55	2.21	0.026
S-S-2	2.66	1.35	1.93	0.025
S-S-3	2.40	1.22	1.74	0.026
S-S-4	2.06	1.05	1.50	0.027
S-S-5	1.85	0.94	1.34	0.026
S-S-6	1.52	0.77	1.10	0.039
S-S-7	1.18	0.60	0.86	0.022
S-S-8	0.92	0.47	0.67	0.028
S-S-9	0.49	0.25	0.36	0.010

*C-S – Circular type - Steady condition, *S-S - Square type - Steady condition



(a) Circular type manhole shape



(b) square type manhole shape

Fig. 2 Two kinds of manhole shapes

upstream, manhole and downstream tank are measured by a tape measure.

Fig. 2 shows the used manhole shapes in this study. Circular and square type manhole shapes are used to estimate head loss effects caused by different manhole shape. The square shape manhole (0.15m×0.15m×1.0m), circular type manhole (Diameter = 0.15m, 1.0m height) and downstream tank are made from transparent acrylic sheet. The manhole part can be separated to replace different manhole shapes by disconnecting the each pipe since this experiment setup was built with the consideration of space and working time efficiency.

3. Experimental conditions

Totally, 20 cases experiments are carried out to estimate head losses at the manhole using circular and square type manholes with no benching and no invert under the steady-state and unsteady-state condition. Each steady-state condition of circular and square case has 9 cases and the experimental case start from about 3.0*l/s* inflow discharge at the upstream with fixed downstream water level at the downstream tank, and the input discharge is gradually decreased by 0.3*l/s* per case, respectively. The selected hydraulic conditions and detail hydraulic parameters are summarized in Table 1. The elevation of bottom of pipe is used as a datum to measure the water level since there is no slope.

After execution of the experiments under the steady-state, unsteady-state condition experiments are carried out in order to estimate the applicability of obtained manhole head loss coefficients. Unsteady-state experiments can be conducted by changing the water level of downstream tank. At first, the downstream water level is maintained with movable gate at downstream, and increased the water level to reach to elevation of 0.5m and then decreased to 0.06m with constantly changing velocity of downstream water level. Same hydraulic conditions are used to both case of circular and square shape manholes and more detail information of unsteady-state condition experiments are summarized in Table 2.

4. Experimental procedures

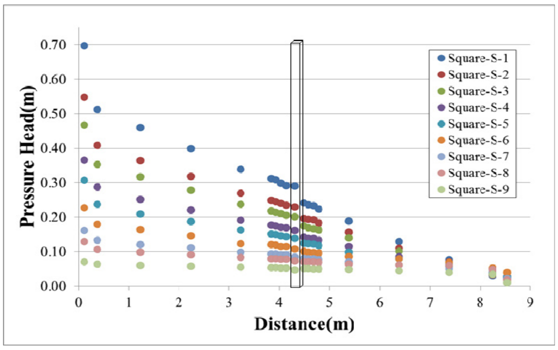
4.1 Steady-state cases

The specified inflow discharge is supplied according to each case and waits until the flow condition becomes steady-state. The waiting time is necessary at least 30 minutes. After that, all measurement points are read from the naked eye and measurements are recorded at piezometric tube panel where all piezometric tubes are getting together with scale bar. But, water levels of each tank and manhole are measured by scale bar which is attached outside of each tank. The number of experiments which are carried out under steady-state condition is 18 cases. All processes are repeated until every experimental case is finished

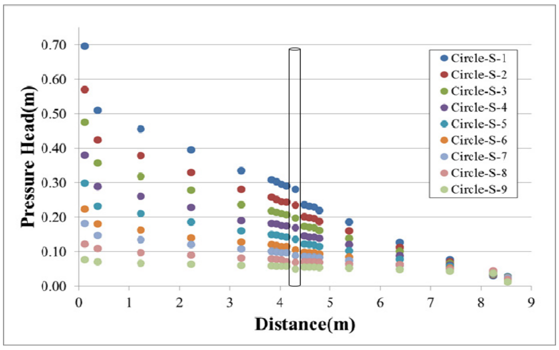
Table 2 Unsteady cases of 2 pipes

Number	Upstream discharge (l/s)	Downstream water level (m)
C-U*	2.13	0.06m-0.50m-0.05m
S-U*	2.13	0.06m-0.50m-0.05m

*C-U – Circular type - Unsteady condition, *S-U – Square type – Unsteady condition



(a) Square shape manhole



(b) Circular shape manhole

Fig. 3 head loss coefficient depending on manhole shape

along with already mentioned steps.

4.2 Unsteady-state cases

The experiments under the steady-state condition are relatively complicated in comparison with the Steady-state condition. First, seven cameras are set in front of upstream tank, manhole, downstream tank and piezometric tubes panel, and then specified discharge is supplied to designated upstream tank with adjustment of downstream water level by controlling a movable gate to set appointed level. A stopwatch is started then all video camera are turned on in order of precedence while recording the time by the stopwatch. Finally, downstream water level is changed by controlling the movable gate at a speed of 0.5mm/sec.

5. Experimental results

The objectives of this study are to recognize the hydraulic characteristics at manhole depending on change of manhole shape, and obtain validation data to verify newly developed numerical simulation model. Head loss coefficients of different types are obtained depending on manhole shapes (circular and square type).

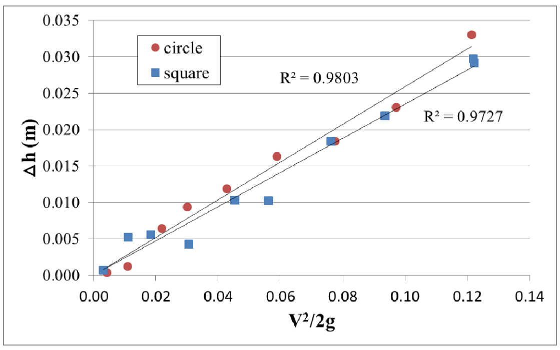


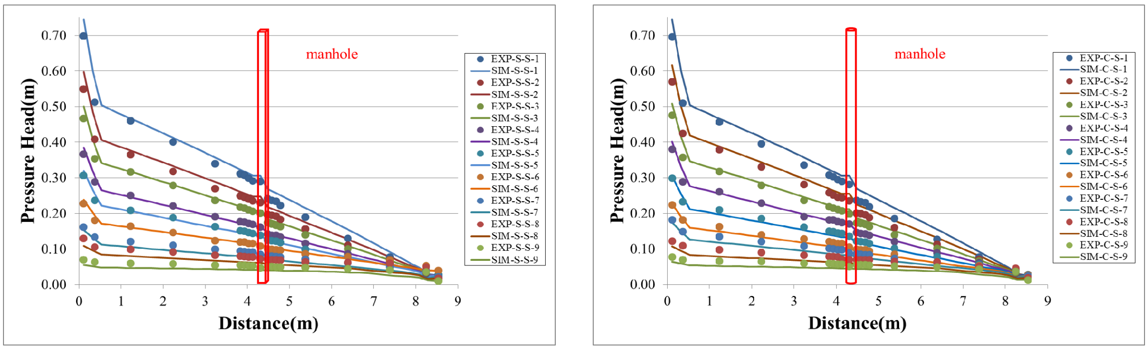
Fig. 4 head loss coefficient depending on manhole shape

Wang et al. (1998) constructed a physical model of a manhole / pipeline system for head loss measurements and conducted a laboratory experiments to determine the head losses at sewer pipe junctions (manholes) under pressurized conditions. They suggested empirical formula which can estimate head-loss coefficients and mentioned that head loss is insensitive to the amount of pressurized discharge, but depends heavily on the configuration of the flow, relative flow rate, and the change of pipe diameter.

To measure the head loss coefficients depending on different manhole shapes, 2 pipes case experiments are conducted under steady-state cases using circular and square type manhole shape and the results of pressure head changes are shown in Fig. 3. As appears out of these graphs, it is clear that pressure head losses occurred at the manhole and it can be calculated by Equation (3.1). The Fig. 4 shows the comparison of relationship between velocity head and pressure head in both cases so that the ratios can be a manhole head loss coefficients. The head loss coefficients obtained are 0.259 and 0.235 for circular and square type manholes, respectively.

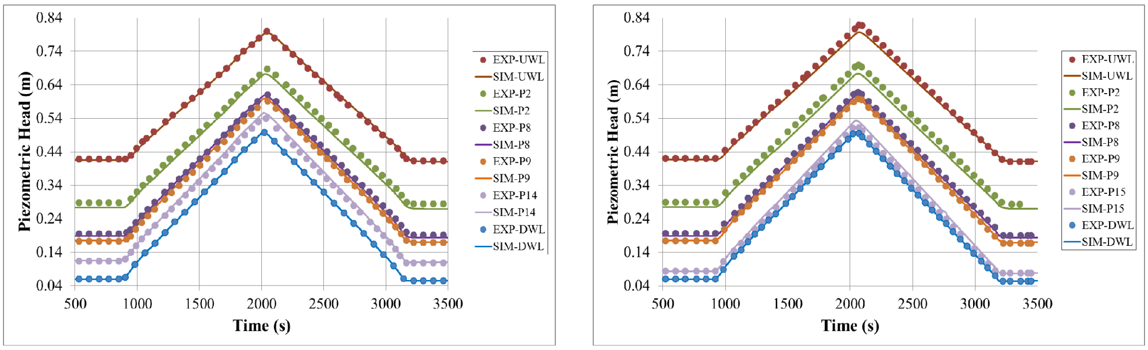
6. 1D sewer pipe model with manhole

6.1 Governing equation for 1D pipe flow



(a) Square shape manhole (b) Circular shape manhole

Fig. 5 Simulated and experimental pressure head of 2 pipes, steady-state cases



(a) Square shape manhole (b) Circular shape manhole

Fig. 6 Simulated and experimental pressure head of 2 pipes, unsteady-state cases

(***UWL** : Upstream Water Level, **DWL** : Downstream Water Level)

The Preissmann slot concept is used to analyze one dimensional unsteady flow in sewer network with manhole. The governing equations of pipe flow are as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2}$$

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

where A is wetted cross section , Q is discharge, q is lateral inflow, u is flow velocity, R is hydraulic radius, H_p is piezometric head ($H_p = z_p + h$), z_p is bottom elevation of pipe and h is water depth in pipe. The water depth h can be calculated by Eq (4).

$$h = \begin{cases} f(A) & : A \le A_0 \\ D + \dfrac{(A - A_0)}{B_s} & : A > A_0 \end{cases} \tag{4}$$

Where f is a function that expressing a relation between flow cross section area and water depth in pipe, A_0 is pipe cross section area, D is pipe diameter and B_s is slot width, determined as follows.

$$B_s = \frac{gA}{a^2} \tag{5}$$

a is a pressure propagation velocity for pipes, and 5.0 m/s is used in this study.

In this research, the shape of pipe is circular type, and circular type hydraulic characteristic formulas are calculated by Equation (6) ~ (8).

$$\phi = 2\cos^{-1}(1 - 2\frac{h}{d}) \tag{6}$$

$$\frac{A}{A_0} = \frac{\phi - \sin\phi}{2\pi} \tag{7}$$

$$\frac{R}{R_0} = 1 - \frac{\sin\phi}{\phi} \tag{8}$$

6.2 Consideration manhole head loss

Manholes in a sewer system behave hydraulically like surge tank (Merlein, 2000).

Therefore next following dynamic equation based on rigid column theory can be used to consider the head loss in the manhole.

$$\frac{\partial Q}{\partial t} = A_p \frac{g}{\Delta x}(\Delta H - \Delta h_1) \tag{9}$$

where A_p is pipe cross-sectional area, H is water elevation of manhole, v is water velocity in pipe and x is a length of the pipe.

The Eq. (9) is used to calculate head losses between manhole and pipes. In addition, continuity equation of Eq. (10) is used to calculate water depth of manhole.

$$A_m \frac{dh}{dt} = Q + \sum_{L}^{M} q_L \tag{10}$$

where A_m is manhole horizontal area, h is water depth of manhole, Q is discharge, M is number of lateral pipes and q_L is lateral inflow to the manhole.

7. Model verification

Numerical model was developed with interaction of combination of 1D momentum equation and dynamic equation based on rigid column theory. In this study, the numerical simulation was carried out with time step of 0.001 second, pressure propagation velocity of 5m/s, Manning coefficient of 0.009 and space steps of 20cm (in pipe) and 15cm (in manhole) in x (longitudinal) directions with various study cases.

Fig. 5 shows the simulated and experimental pressure head profiles at different piezometric tubes according to different manhole shapes under the steady-state condition. It is clear that the pressure head profiles are changed before and after passing the manhole since head losses were occurred at the manhole.

Consequently, all simulation results in Fig. 5 shows good agreement with experimental results even there are small miss matching in the case of C-S-1 and S-S-1.

Johnston and Volker (1990) mentioned that an influence of Froude number and manhole submergence are not major, but nevertheless are important in some flow condition. The Froude numbers of C-S-1 and S-S-1 are 4.86 and 4.89, respectively. It indicates that their flow conditions are supercritical flow and their approaching speed to the manhole is relatively very fast than other cases, and it causes a fluctuation in the manhole. Actually, the fluctuation have been reported a range of ±0.1mm ~ ±20.0mm by Johnston and Volker (1990). Therefore these simulation results are acceptable if experimental observation errors caused by the fluctuation are allowed.

Fig. 6 shows the simulated and experimental pressure head profiles at different piezometric tube according to manhole shape difference under the unsteady-state condition. Measurement points, upstream tank, pipe segment No.2, No. 8, No. 9, No. 14 and No. 15, are selected to measure the change of piezometric head according to time variation. In this experiment, an input discharge was selected as 2.13*l/s* in order to improve experimental observation accuracy and reduce fluctuation at the manhole as reducing the Froude number.

Unsteady-state condition was made by controlling downstream movable gate, which may reflect ascending and descending a water level of river in real case. The head loss coefficients obtained through the experimental data analysis are used same with steady-state experiments, and all simulation results showed good agreement with experimental data.

8. Conclusions and recommendation

In this study, fundamental laboratory experiments are carried out using different manhole shapes (circular and square) with no benching and no invert in order to estimate the effects of head loss depending on different manhole shapes.

First, straight cases were conducted in order to evaluate the head loss depending on manhole shape between circular and square type and then numerical model was developed and validated to confirm an applicability of the model using head loss coefficients based on experimental data from laboratory experiments. The main findings in this study are described as follows:

1. In two pipes cases, Head loss coefficient shows constant values regarding to manhole shapes, and each coefficient is obtained as 0.259 and 0.235

for the circular and square type manhole shapes, respectively.

2. 1D numerical model was developed for computing the hydraulic characteristics of pipe flow with manhole. The proposed model consists of general governing equations and dynamic equation to effectively consider the head loss due to the different manhole shapes.

3. All simulation results showed good agreement with experimental results under not only steady-state but also unsteady-state conditions.

However the model application to real basin and laboratory scale experiments under various conditions are still remained as a task to be performed. There are many things that should be consider to simulate and predict urban sewerage system such as various pipe configuration, pipe slopes, interaction between ground surface and sewerage system etc. This study is conducted under very simple circumstance in order to develop the reasonable model which can reflect head loss caused by different manhole shapes.

Therefore, in the next study, more realistic experiments are needed under the already mentioned various conditions in order to improve the model.

Acknowledgements

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