

Article

Head Loss Reduction in Surcharged Four-Way Junction Manholes

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Received: 2 October 2018; Accepted: 24 November 2018; Published: 27 November 2018



Abstract: Head loss in surcharged four-way junction manholes is a factor that increases damage due to urban inundation; thus, the flow characteristics of such manholes must be analyzed to reduce the head loss. In this study, a physical model was constructed; this model included a manhole and a connection pipe, fabricated on a 1/5 scale by applying sewer facility standards to perform a physical model investigation. Numerical simulations were performed using the Fluent model to derive efficient benching designs that can reduce head loss. Physical model investigations were performed by varying the ratio of the lateral influent flow rate to the effluent flow rate as well as by varying the effluent flow rate and benching designs. The result of physical model investigations showed that the installation of half rectangular benching reduced the head loss coefficients by 7% and 10% on average compared with square and circular manholes, respectively. The installation of full rectangular benching reduced the head loss coefficients by 28% and 17% on average compared with square and circular manholes, respectively. Thus, the benching proposed herein can be installed and used to improve the drainage capacity of urban stormwater conduit facilities.

Keywords: drainage facility; four-way junction manhole; benching design; surcharge flow

1. Introduction

Localized heavy rainfall in urban areas commonly leads to damage due to inundation in lowlands, where the drainage rate sharply increases [1], as well as in areas with poor sewage systems or insufficient drainage capacity [2,3]. Rainwater in urban areas drains through stormwater conduit facilities in the drainage system; hence, it is essential to increase the rainwater drainage capacity of drainage systems for preventing urban flooding [4–6]. Conduit facilities include conduits, manholes, storm overflow diverging tanks, gutters (including sewage, stormwater, and catchment gutters), and connection pipes. According to Dick et al. [7], a manhole must be installed where the starting point, direction, slope, or diameter of the pipe changes, and where a step is generated, where pipes combine, or where pipe maintenance is necessary. Manholes are classified by shape, either standard (circular) or special (square). Furthermore, depending on the joint shapes in the inflow pipe, outflow pipe, and manhole, manholes are divided into middle manhole (in which one inflow pipe and one outflow pipe are arranged in a straight line) and junction manholes (in which the inflow and outflow pipes are not arranged in a straight line or two or more inflow pipes and one outflow pipe are joined to the manhole). Drop manholes are widely implemented in drainage networks for steep urban catchments, where the topography induces excessively high flow velocities [8]. In addition, bend manholes in sewer systems are often used in urban areas, because sewers usually follow city road systems. Of particular relevance are 45° and 90° deflections [9].

Analyzing the flow characteristics in a manhole is crucial to reducing head loss and improving drainage capacity. These analyses are necessary for developing reasonable head loss reduction plans and maintenance standards, as well as effective installation and design criteria. According to the inundation trace map provided by the Seoul Metropolitan Government in South Korea, inundation mainly occurs in the downstream of drainage basins in urban areas caused by the excess of the discharge capacity for manhole overflows. A four-way junction manhole is a type of conduit facility mainly installed in the downstream areas of drainage basins that directly affects the inundation of downstream urban areas. The head loss at surcharged four-way manholes has a significant impact on the conduit facility drainage and reduces the drainage capacity of the stormwater conduit systems [10,11]. Experimental studies are continuously being conducted on physical models equipped with a change of benching floor configuration (e.g., flat, half, full) for reducing head loss in middle and junction manholes, whereas little research is being performed on the head loss reduction in a four-way junction manhole. Moreover, no studies have analyzed the applicability of the benching design (e.g., the deflection angle and the alignment of pipes) via comparing a physical model investigation with a numerical simulation.

Studies calculating the head loss coefficient of manholes have been conducted since the 1950s, and head loss reduction in surcharged manholes has been investigated since the 1980s. Marsalek [12] conducted experiments to calculate the head loss coefficients in the square and circular middle manholes and compared the head loss coefficients of manholes according to the benching floor configuration. Arao and Kusuda [13] examined drop gaps and benching floor configuration changes in circular manholes during downstream inundation and calculated the head loss coefficients of manholes based on their depth. Merlein [14] calculated the head loss coefficient with a change in the influent flow rate in an experiment, in which a full benching was installed inside middle circular manholes and a cover plate was installed on the manhole. Granata et al. [8] and Zheng et al. [15] conducted a physical model investigation of a circular drop manhole to study the energy dissipation with three basic flow patterns or three drop heights. They showed various parameters that affect the hydraulic performance of the drop manhole to improve the design, and then proposed the empirical equations to apply each parameter. The Federal Highway Administration (FHWA) [16] presented a head loss coefficient formula that depended on the connection angle between the manhole and pipe, the ratio between the diameters of the connection pipe and the manhole, the manhole depth ratio, and the benching floor configurations change. Nevertheless, no studies have yet presented a head loss coefficient formula for four-way junction manholes.

Several studies investigated head loss reduction in surcharged junction manholes. Lindvall [17] assumed that a three-way junction manhole consisting of two inflow pipes and one outflow pipe was in a surcharged state and calculated the head loss in which the benching floor configuration was divided into half and full. Marsalek and Greck [18] conducted experiments, in which the ratio of the manhole width to the diameter of the connecting pipe in square and circular manholes was set to 2.26 and 4.6, respectively; a benching was installed inside the manhole, or the shape of the manhole was varied. They investigated measures for reducing the head loss coefficient by considering changes in the manhole shape and connection pipe diameter, and they obtained head loss coefficients of 1.73 and 1.52 for square manholes and 1.80 and 1.87 for circular manholes. Johnston and Volker [19] calculated the head loss coefficient of a middle manhole and confirmed head loss reduction caused by the installation of a benching inside the manhole. They also calculated the head loss coefficients with changing influent flow rate and presented an experimental equation for a surcharged junction manhole, in which two inflow pipes with different connection pipe diameters and one outflow pipe were joined. They determined the reduction in head loss resulting from the installation of a deflector in the junction manhole. Wang et al. [10] studied the head loss coefficient of four-way circular junction manholes, in which three inflow pipes were joined to one outflow pipe. The study presented the head loss coefficient for various influent flow rate ratios of the three inflow pipes by varying the size of the manhole and the diameter of the connecting pipe after installing a half benching inside the manhole.

From the conducted literature survey, physical model conditions were selected for calculating the head loss coefficient of surcharged four-way junction manholes and for deriving head loss reduction methods for them. A physical model was constructed based on the physical model conditions, and a physical model investigation was performed to calculate the head loss coefficients with and without cross-shaped benching (half or full) installed in a surcharged four-way junction manhole. Furthermore, the flow pattern changes in the manhole caused by the benching design change were simulated, and an efficient benching design was derived using a three-dimensional flow analysis (i.e., the Fluent 6.3 model) to determine the benching design that reduces the head loss coefficient in a surcharged four-way junction manhole. An efficient benching design derived from the numerical simulations was then constructed and installed in surcharged four-way junction manholes to conduct a physical model investigation to verify the head loss reduction. The result of the physical model investigations was used to calculate the head loss coefficient with and without the efficient benching (i.e., half and full rectangular) installed in the surcharged four-way junction manhole. Finally, the calculated head loss coefficients were compared to propose an efficient benching design that can reduce the rise in the head loss coefficient caused by vortices.

2. Theoretical Background

2.1. Head Loss Coefficient of a Surcharged Junction Manhole

The flow of each pipe connected to a manhole under surcharge flow conditions is the pressure flow. The total head H at each point of the joint is composed of the hydraulic grade line head and the velocity head. The energy equation applied by Wang et al. [10] is used to calculate the head loss coefficient of a surcharged junction manhole with three inflow pipes and one outflow pipe. In this equation, the hydraulic grade line head is the sum of the pressure head p/γ and the potential head z . The flow continuity equation is $Q_o = Q_m + Q_a + Q_b$. The head loss in the surcharged four-way junction manhole is shown in Equation (1). This equation is derived by applying the continuity equation to the energy equation.

$$\frac{\Delta E}{\rho g} = Q_m \Delta H_m + Q_a \Delta H_a + Q_b \Delta H_b \quad (1)$$

where ΔH_m , ΔH_a , and ΔH_b refer to the head loss corresponding to the main connection pipe and lateral connection pipes A and B, respectively, which are calculated as shown in Equations (2)–(4), respectively.

$$\Delta H_m = \left(h_m + \frac{V_m^2}{2g} \right) - \left(h_o + \frac{V_o^2}{2g} \right) \quad (2)$$

$$\Delta H_a = \left(h_a + \frac{V_a^2}{2g} \right) - \left(h_o + \frac{V_o^2}{2g} \right) \quad (3)$$

$$\Delta H_b = \left(h_b + \frac{V_b^2}{2g} \right) - \left(h_o + \frac{V_o^2}{2g} \right) \quad (4)$$

where K_i ($i = m, a, b$), the dimensionless head loss coefficient at each joint pipe, is calculated by each head loss term ΔH_i ($i = m, a, b$) and the velocity head $V_o^2/2g$ of the outflow pipe is shown in Equation (5).

$$K_i = \Delta H_i / \frac{V_o^2}{2g} \quad (5)$$

Equations (2)–(5) are substituted into the continuity equation and reorganized to obtain K , which is the total head loss coefficient of a surcharged four-way junction manhole, as shown in Equation (6) [10]

$$K = \frac{Q_m}{Q_o} K_m + \frac{Q_a}{Q_o} K_a + \frac{Q_b}{Q_o} K_b \quad (6)$$

2.2. Physical Model Investigation

2.2.1. Construction of the Physical Model

Previous studies showed that in surcharged manholes, the separation zone at the corners of the manhole increased and the drainage capacity decreased as the ratio of the manhole size D to the joint pipe diameter d increased [17,18,20–22]. Considering these results, the largest joining ratio condition ($D/d = 3.0$) was selected among the installation standards proposed by the Ministry of Environment (MOE) in Korea [23]. Previous studies showed that the sizes of the inlet and outlet pipes affect the pressure change [24] and that the head loss coefficient decreases with the manhole width [12,22]. Therefore, this study selected standard No. 1 manholes (900 mm in diameter or 900 mm width and 900 mm length) together with drainage pipes with a minimum pipe diameter of 300 mm, as proposed by the MOE [23]. In this study, a 1/5 physical model of the manhole and joint pipes were constructed.

The fabricated physical model consisted of a high-water tank, constant head tanks A, B, and C, acrylic pipes (60 mm in diameter), acrylic manholes (180 mm in diameter or 180 mm \times 180 mm), a manometer, and an intercepting container. The inflow and outflow pipes were at least 4500 mm long to stabilize the flow in the pipeline. The head loss values in the manhole and the velocity head of the outflow pipe must be determined to calculate the head loss coefficient in the four-way junction manhole. As shown in Figure 1, the head loss at the manhole was calculated using the change in pressure heads in the pipes and the velocity head value measured in each connection pipe (main inflow, lateral inflow, and outflow pipes). Thus, the changes in the pressure heads in the pipes were measured using a piezometer installed at 300 mm intervals in each inflow pipe. Piezometers were densely installed at 100 mm intervals to more closely measure the pressure head changes before and after the joint with the manhole. Moreover, the velocity head was calculated by converting each measured flow rate, after installing a flow meter onto the inflow pipe. An intercepting container with a width of 1000 mm, a length of 1000 mm, and a height of 400 mm was installed to measure the effluent flow rate.

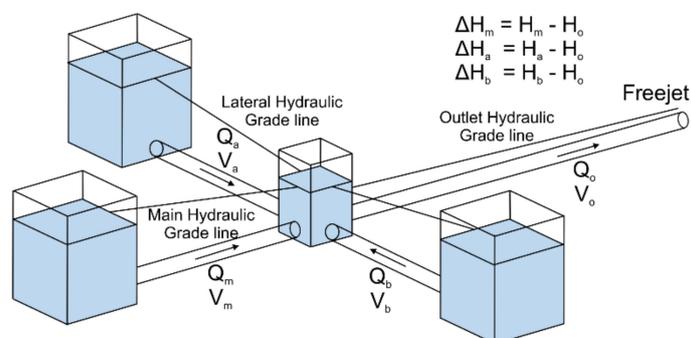


Figure 1. Schematic of the physical model.

The experimental flow rates of 2.0, 3.0, 4.0, and the maximum experimental flow rate of 4.8 ℓ/s without overflowing manholes were selected to analyze the changes in the head loss coefficients resulting from the flow rate changes in the four-way junction manhole. The flow characteristics and the head loss coefficient in the four-way manholes differed with the changes in the main and lateral influent flow rate ratios. Thus, the manhole flow characteristics must be analyzed with respect to the change in the lateral flow rate ratio (the ratio of the lateral influent flow rate $Q_{lat} = Q_a + Q_b$ to the effluent flow rate Q_{out}). In the physical model investigations, Q_{lat}/Q_{out} was varied from 0.0 to 1.0. Table 1 shows the investigational conditions, while Table 2 shows the lateral flow rate ratio for each influent and effluent flow rate.

Table 1. Investigational conditions.

Manhole Shape	Manhole Size (mm)	Pipe Diameter (mm)	Effluent Flow Rate (ℓ/s)	Reynolds Number	Lateral Flow Rate Ratio(Q_{lat}/Q_{out})	Flow Condition
Square	180 × 180	60	2.0, 3.0,	37,000, 56,000,	0.00, 0.25, 0.50, 0.66, 0.75, 1.00	Steady
Circular	180		4.0, 4.8	75,000, 81,000		

Table 2. Flow rate with respect to the change in the lateral flow rate ratios.

Effluent Flow Rate (ℓ/s)	Influent Flow Rate (ℓ/s)	Lateral Flow Rate Ratio (Q_{lat}/Q_{out})					
		0.00	0.25	0.50	0.66	0.75	1.00
2.0	Q_m	2.00	1.50	1.00	0.67	0.50	0.00
	Q_a	0.00	0.25	0.50	0.67	0.75	1.00
	Q_b	0.00	0.25	0.50	0.67	0.75	1.00
3.0	Q_m	3.00	2.25	1.50	1.00	0.75	0.00
	Q_a	0.00	0.38	0.75	1.00	1.13	1.50
	Q_b	0.00	0.38	0.75	1.00	1.13	1.50
4.0	Q_m	4.00	3.00	2.00	1.33	1.00	0.00
	Q_a	0.00	0.50	1.00	1.33	1.50	2.00
	Q_b	0.00	0.50	1.00	1.33	1.50	2.00
4.8	Q_m	4.80	3.60	2.40	1.60	1.20	0.00
	Q_a	0.00	0.60	1.20	1.60	1.80	2.40
	Q_b	0.00	0.60	1.20	1.60	1.80	2.40

2.2.2. Head Loss Coefficients at the Surcharged Manhole without Benching

The head loss coefficient for manholes without benching (Figure 2) was calculated to compare the head loss changes with the benching designs using the physical model and the investigational conditions in the previous section.

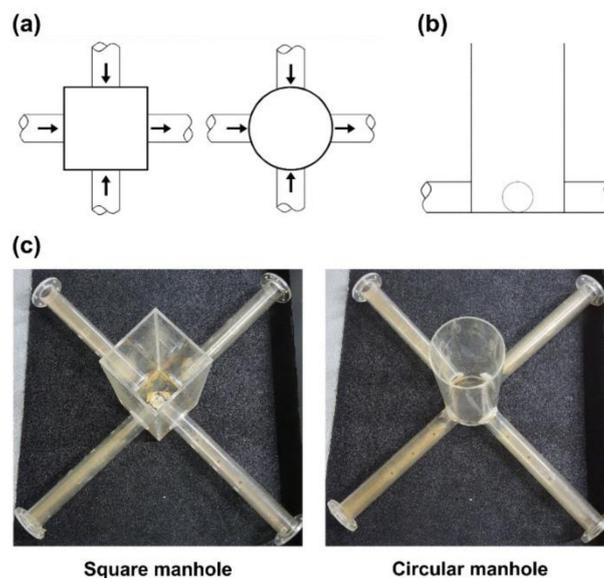


Figure 2. Manhole model without benching. (a) Schematic of without benching. (b) Manhole cross-section. (c) Manhole model.

The pressure heads of the main inflow, lateral inflow, and outflow pipes of the physical model were measured to calculate the head loss ΔH in the manhole with respect to the changes in the influent flow rate. The measured head loss values were connected along a linear trendline to measure the head loss occurring at the inflow and outflow of the manholes. The measured head loss values and

the average flow rate in each pipe were applied to Equation (5) to calculate the change in the head loss coefficients with the changes in the lateral flow rate ratios, which were classified into square and circular junction manholes in (Figure 3).

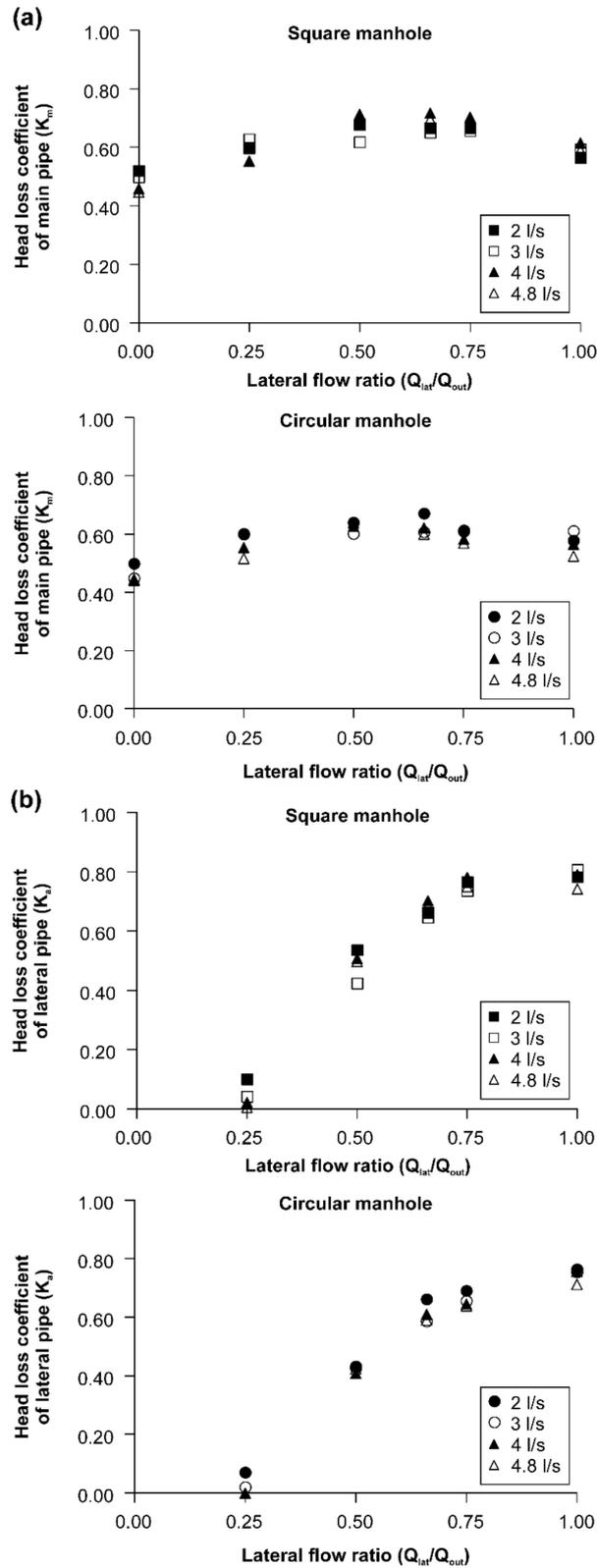


Figure 3. Change in the head loss coefficients of the junction manhole with respect to the changes in the influent flow rate ratio. (a) Head loss coefficient of the main pipe. (b) Head loss coefficient of the lateral pipe.

The results showed that the head loss coefficient in the main pipe was 0.6 on average, regardless of the lateral flow rate ratio. The results suggested that the head loss in the main flow was not significantly affected by the change in the lateral flow rate ratio. However, the head loss coefficient of the lateral pipe rapidly increased as the lateral flow rate ratio increased. The head loss coefficient values ranged from 0.0 to 0.8, except in the absence of an influent flow. This result indicated that the head loss in the four-way junction manholes increased because of the influence of the flow collision induced by the inflow of the two lateral pipes as the lateral influent flow increased. Furthermore, these results confirmed that the head loss coefficient calculated with respect to the change ratio of the lateral flow rate was relatively constant, regardless of the increase in the Reynolds number caused by the flow rate changes in the outflow pipe. The head loss coefficient and the influent flow rate values measured and calculated from the main and lateral pipes were substituted into Equation (6); in this way, the head loss coefficient K in a surcharged four-way junction manhole was calculated. Figure 4 shows the total head loss coefficient with the changing lateral influent flow rate ratios.

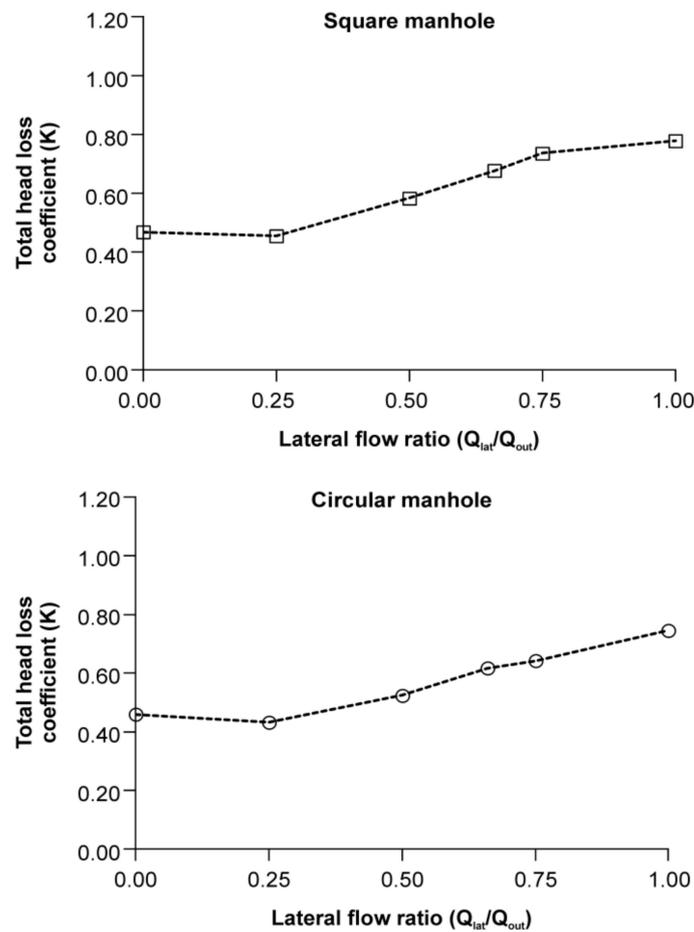


Figure 4. Total head loss coefficient of the surcharged four-way junction manhole with respect to the influent flow rates ratio.

2.2.3. Head Loss Coefficient Change in the Cross-Shaped Benching Installation

Although the FHWA [16] presented benching floor configurations for improving the flow and drainage capacity of a manhole, the design of four-way junction manhole benching has not been presented. Moreover, only a few physical model studies have been conducted on the head loss reduction in surcharged four-way junction manholes. Thus, using cross-shaped benching (Figure 5) obtained by applying the benching floor configurations presented by the FHWA [16] to four-way junction manholes, the half benching of half the size of the connection pipe and the full benching of

the same size as the connection pipe were fabricated and installed in four-way junction manholes to analyze their influence on manholes. Similar to the manhole models, the benching was made of acrylic. Figure 6 presents the benching installed in the manhole models.

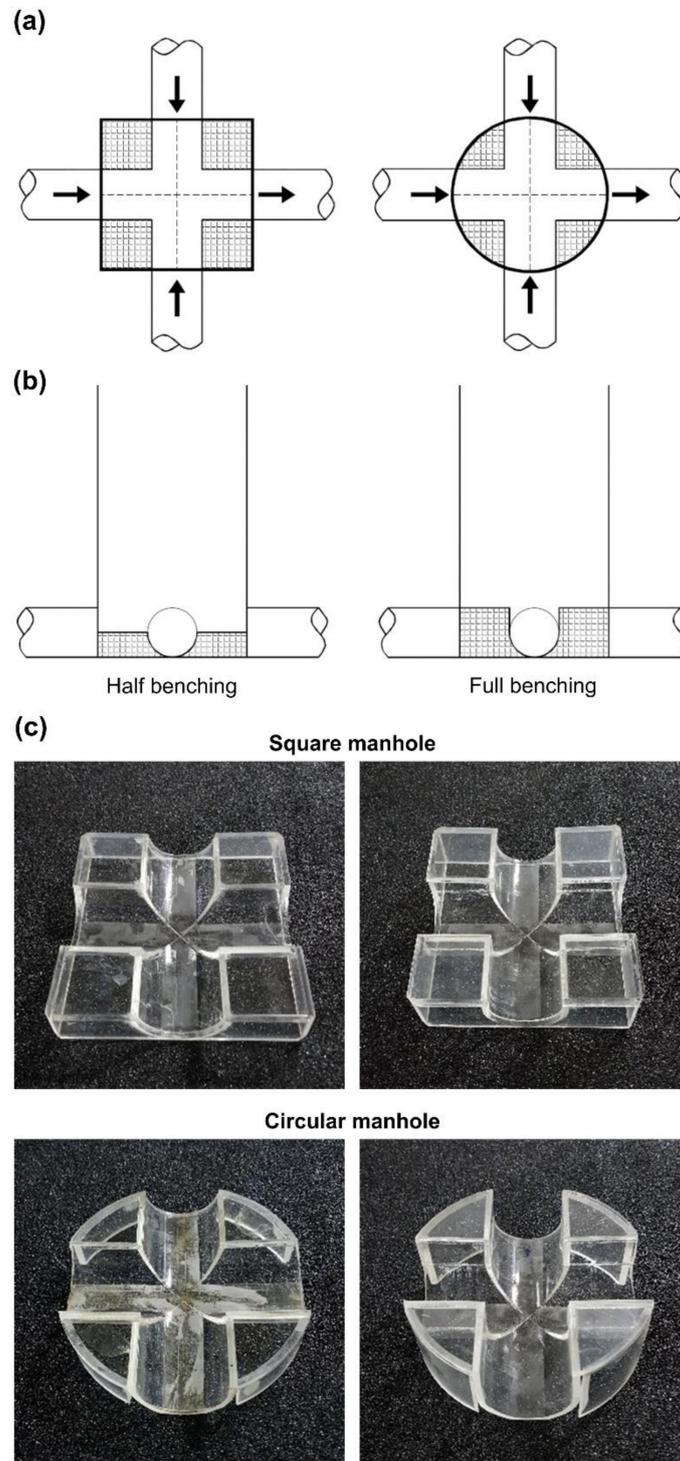


Figure 5. Cross-shaped benching. (a) Schematic of installed benching. (b) Benchings cross-section. (c) Cross-shaped benching model.

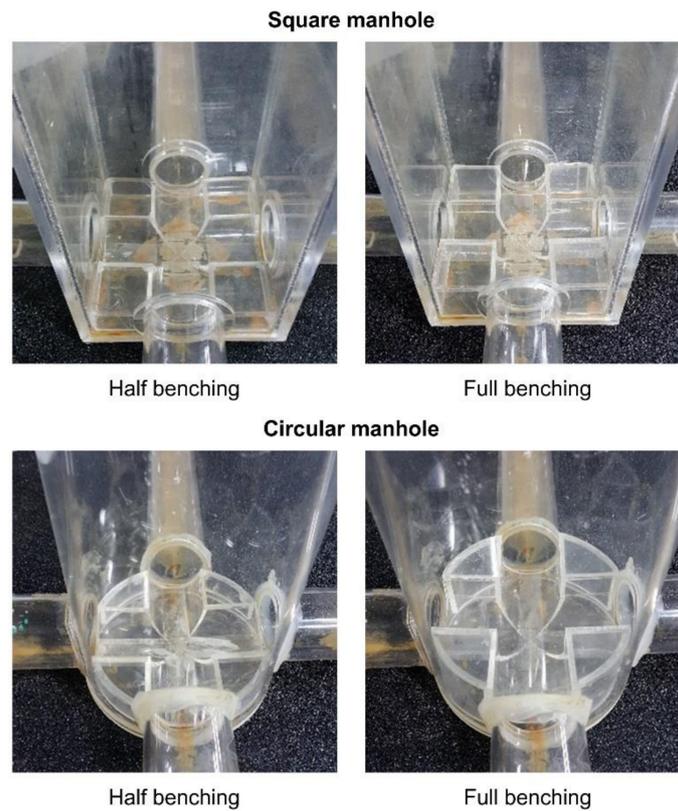


Figure 6. Benching installed in the manhole.

A physical model investigation was performed under the same conditions listed in Tables 1 and 2 to compare and analyze the head loss coefficient in four-way junction manholes without benching (Figure 4). The result of the physical model investigations showed that the increasing tendency in the head loss coefficient with the lateral flow rate ratio was the same, regardless of the type or benching installation. However, the results showed that the half and full cross-shaped benching reduced the drainage capacity of the four-way junction manhole instead of increasing it. In comparison with the total head loss coefficient of the manhole without benching, the total head loss coefficient of the cross-shaped benching was the same when the lateral flow rate ratio was 0.25 or less. However, their head loss coefficient gradually increased to more than that of the manholes without benching when the lateral flow rate ratio was 0.5 or more. At a lateral flow rate ratio of 1.0, the total head loss coefficient of the manholes with the half and full cross-shaped benching was approximately 25% and 37%, respectively, more than that of the total head loss coefficient of the manholes without benching (Figure 7).

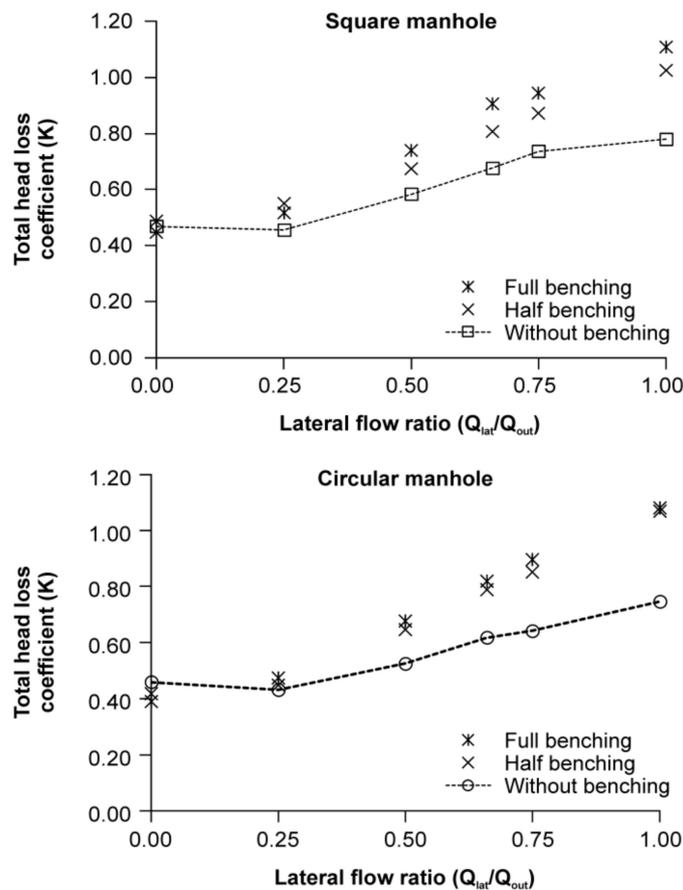


Figure 7. Change in the head loss coefficient of manhole with cross-shaped benching.

When a cross-shaped benching was installed, the flow interference at the cross-shaped benching intersection was small when the inflow into the main pipe was larger than the inflow into the lateral pipe. However, the inflow into each lateral pipe collided at the cross-shaped benching intersection when the inflow into the lateral pipe was larger than the inflow into the main pipe, creating a large flow interference. In this case, the large flow interference increased flow stagnation and increased the head losses in the four-way junction manhole. Hence, the installation of a cross-shaped benching should be avoided because it reduces the drainage capacity in the surcharged four-way junction manhole. Moreover, an efficient benching design is required to increase the drainage capacity.

2.3. Numerical Simulation for Deriving an Efficient Benchng Design

2.3.1. Mesh Grid Configuration of the Fluent Model

The physical model investigation in the previous section showed that cross-shaped benching reduced the drainage capacity of the junction manholes. The surcharged flow in manholes in this study had multiphase water and air flow and caused a complex flow condition in manholes. Thus, three-dimensional flow simulations were performed using a Fluent model to derive an efficient benching design that induces flow in a four-way junction manhole. The Fluent 6.3 model [25], a three-dimensional finite volume, numerical model in a graphical user interface (GUI) environment, was used for the numerical simulations reflecting the multiphase and for the hydrodynamic modeling of fluid mechanics, heat transfer, and chemical reactions. In solving hydrodynamic problems, this study uses the volume of fluid (VOF) method for free surface analysis, which is a method of for analyzing the behavior of multiphase fluids.

The flow velocity of the inflow and lateral inflow pipes was set to 0.57 m/s to compare the physical model investigation and numerical simulation results. The manhole and connection pipes were constructed in the same mesh grid as the investigational conditions as the same purpose.

The VOF scheme was applied to analyze the flow characteristics and the multiphase flow in the manholes. The numerical methods included unsteady flow equations, the first-order implicit method for nonuniform flow formulation, the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) method for pressure and velocity coupling, and the first-order upwind scheme for discretization. The $k - \varepsilon$ turbulence model was used to calculate the turbulent flow and introduce the transfer equation of the turbulent kinetic energy k and the turbulent energy dissipation rate ε . Standard wall functions were used. The mesh grid of the manhole and the connecting pipe was composed of a tetrahedron grid at the confluence of the manhole and the connecting pipe and a hexahedron grid elsewhere to stabilize the numerical analysis. The sides of each grid took the form of a possible tetragon or triangle. The number of grids according to the mesh configuration was 695,901 (Figure 8). The wall (no-slip) boundary condition was applied to the wall of the manhole model. The velocity condition was applied to the inflow portion, and the atmospheric condition was applied to the boundary between the outflow and the free surface of the manhole.

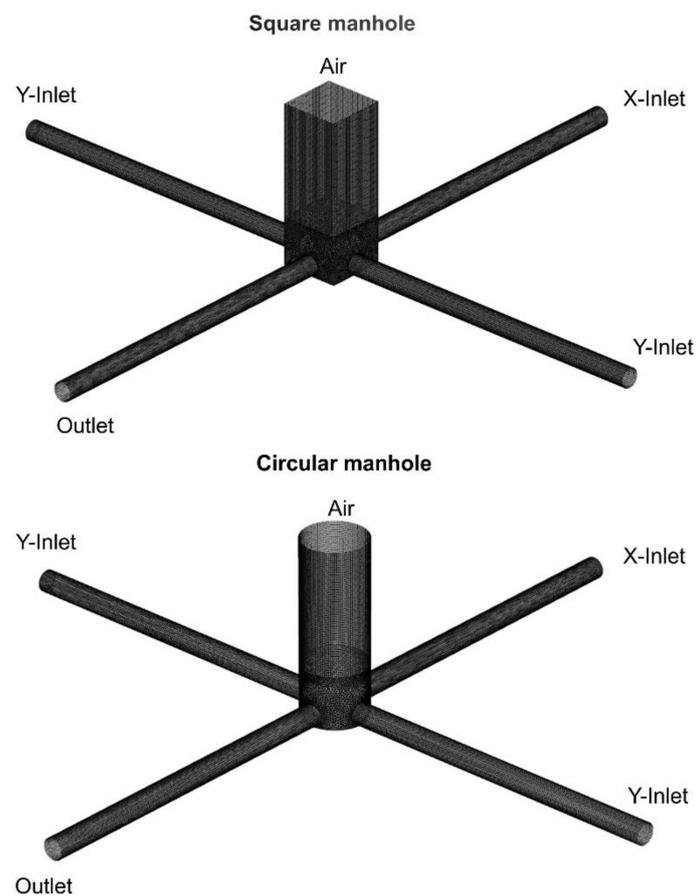


Figure 8. Manhole mesh grid configuration.

2.3.2. Flow Simulation in the Four-Way Junction Manhole without Benching

The physical model investigations in the previous section showed that the benching design and floor configuration influenced the head loss and drainage capacity of the four-way junction manhole. Thus, the main flow direction (inflow to outflow), which was not confirmed in the experiment, and the position and height of the vortices in the manholes were analyzed through a numerical simulation. Figure 9 shows the analysis result of flow pattern in the four-way junction manhole without benching, as a vector and a streamline.

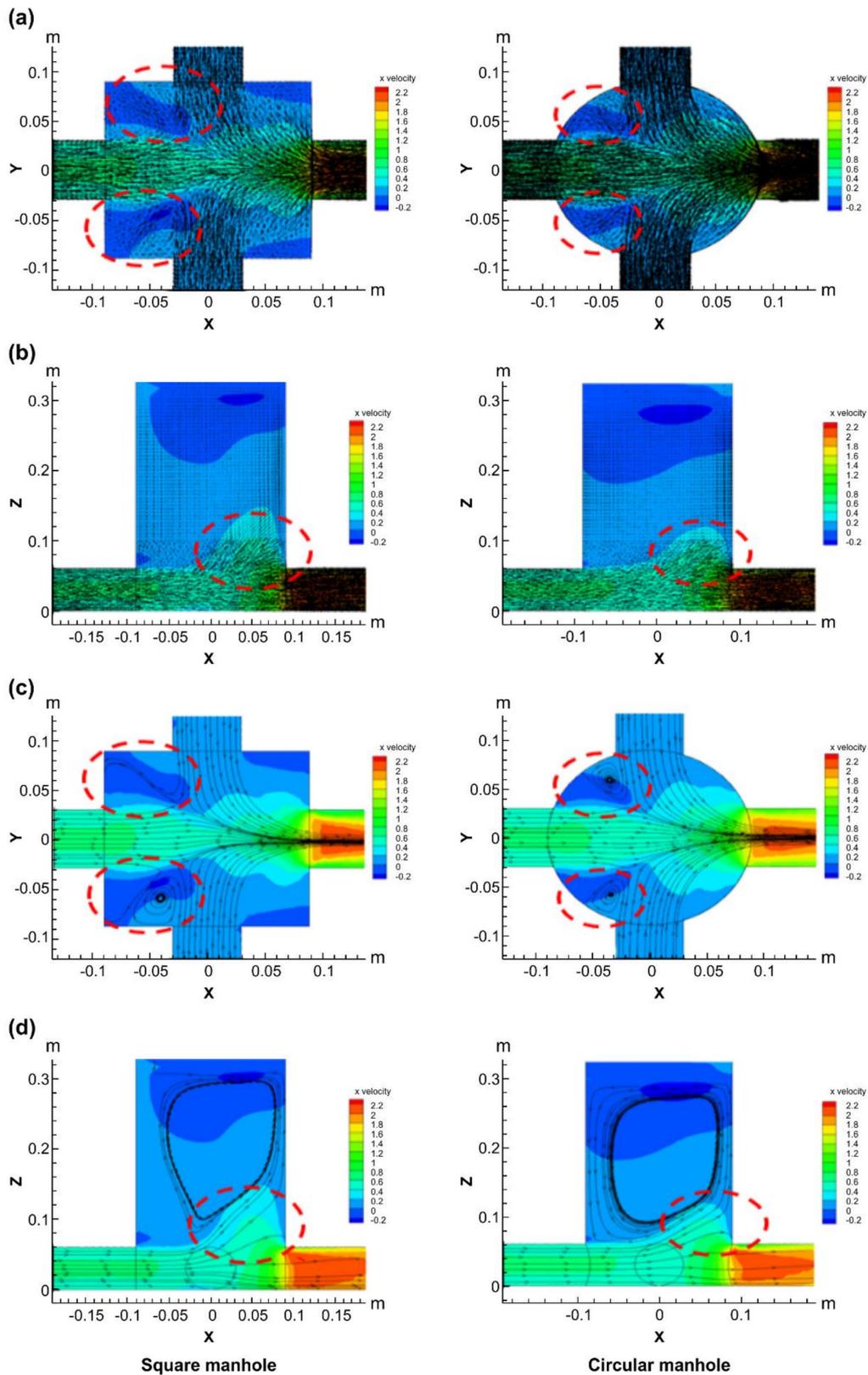


Figure 9. Numerical simulation results of the manhole without benching. (a) Vector diagram of X–Y plane. (b) Vector diagram of X–Z plane. (c) Streamline of X–Y plane. (d) Streamline of X–Z plane.

The X–Y cross-sectional vector diagram in Figure 9a reveals that a separation zone occurred in the simulation. The separation zone showed a low-velocity section with a flow velocity in the X direction

less than 0.2 m/s at the corners of the four-way manhole, which corresponded to both the corners of the main pipe joint and the outflow pipe joint. Furthermore, the X–Z cross-sectional vector diagram in Figure 9b illustrated that the joint between the manhole and the outflow pipe exhibited a vertical upward flow trend. The analysis showed that the main and lateral pipe inflows rose to the upper joint, failing to flow out through the outflow because of the flow concentration phenomenon induced by the flow collision approximately 50 mm from the outflow of the manhole. The rate of the upward flow was as high as 0.6 m/s, inducing a vertical vortex.

The simulated flow pattern in the four-way junction manhole was similar for the square and circular manholes. However, as shown in the X–Y cross-sectional vector diagram and streamline in Figure 9a,c, the drainage flow was relatively improved because the low-flow velocity section of 0.2 m/s in the circular manhole was less distributed compared to the low-flow velocity section in the square manhole. The flow in the vertical direction occurring from the X–Z cross-sectional vector diagram showed that the high-flow velocity (0.6 m/s) section rising toward the top of the circular manhole was less distributed compared to high-flow velocity section in the square manhole. Thus, the flow immediately draining through the circular manhole was higher than that through the square manhole.

2.3.3. Flow Pattern Analysis for Deriving an Efficient Benching Design

As described in the previous section, the numerical simulations of a manhole without benching showed that the flow velocity decreased, and vortices occurred at the corners of the joint between the manhole and the pipes, leading to a drainage interference. The flow characteristics should be improved by considering these numerical simulation results to decrease vortices from occurring in manhole. Thus, four benching design types (Figure 10) were selected to minimize water impingement, vortices, and the separation zone occurring at the corners, to prevent the drainage capacity from decreasing because of a collision in the flow directions caused by the conflicting orientations of the benching design, and to derive efficient benching design for flow improvement in the surcharged four-way junction manholes. The numerical simulations of the square and circular manholes showed that the drainage interference in the square manhole was larger than that in the circular manhole. Thus, benching design in a numerical simulation was prepared by analyzing the improvement effects only in the square manholes. The same design was then applied to the circular manholes in the physical model investigation. As shown in (Figure 10), Design 1 was designed to improve flow by preventing contradiction in the three-way junction flow and manipulating the lateral flow direction toward the outflow. Design 2 was designed to allow the flow directions to contradict by differentiating the curvature of the induction channels, reducing the phenomenon in which simultaneous contradictory influent flows increase the vortex occurrence. Design 3 was designed to minimize the space where vortices induced in the separation zone occur at each corner. Design 4 was designed to prevent vortices and minimize the inundation of the manhole volume caused by benching.

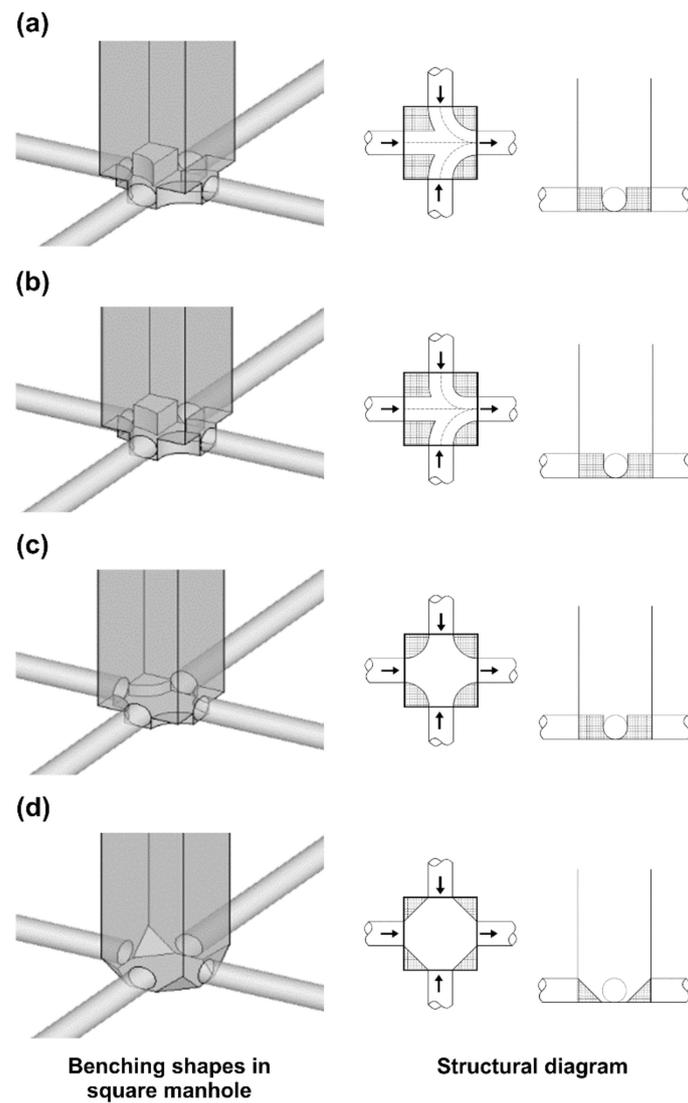


Figure 10. Benching design types: (a) Design 1; (b) Design 2; (c) Design 3; and (d) Design 4.

A numerical simulation was performed to analyze the flow pattern in the four-way junction manholes caused by the installation of the benching in each of the four designs. This study aimed to select the most efficient benching design considering the vortex reduction in the horizontal and vertical directions and the water depth reduction in the junction manholes. Figure 11 shows the numerical simulation results of the four types of benching to improve the vortex reduction and separation zone flow in the manholes.

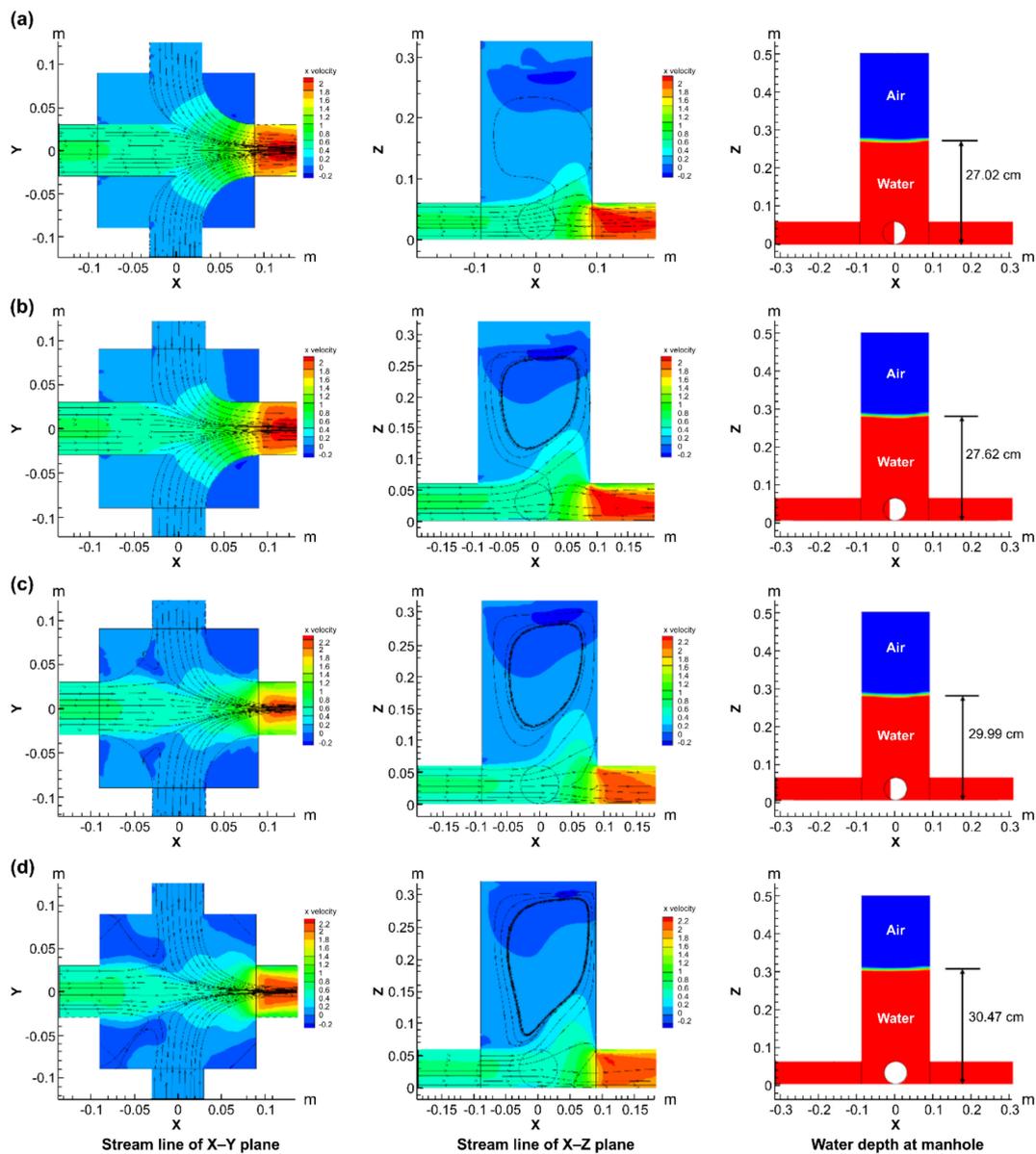


Figure 11. Numerical simulation results on square junction manholes considering the benching design: (a) Design 1; (b) Design 2; (c) Design 3; and (d) Design 4.

Designs 1–3 showed improvement in the separation zones that occurred on both sides of the main pipe inflow in the square manhole without benching. However, Design 4 showed no improvement at the same location. The X–Y streamline diagram illustrated that Design 1 significantly reduced the vortices that occurred in the vertical direction, whereas such vortices consistently appeared in Design 2–4. Furthermore, as regards the head loss and the drainage capacity improvement in the surcharged square manhole, the water depth in Design 1 was the lowest (Figure 11). Thus, Design 1 showed the highest flow improvement by inducing the direction of the lateral.

3. Results and Discussions

3.1. Applicability Analysis of the Benching

A physical model investigation was performed to quantitatively verify the effects of the four benching on flow improvement based on the obtained numerical simulation results. The numerical simulation results indicated that Design 1 had the highest flow improvement effect; hence, acrylic

benching models were fabricated based on it. Furthermore, models were fabricated, and investigations were performed for Design 3 and Design 4 to compare and verify the head loss reduction effects. A physical model investigation on Design 2 was not performed because no significant effect was confirmed through numerical simulations, and the increase in the water depth suggested that Design 2 had no significant effect on the head loss reduction. Figure 12 shows the design of the benching models and their installation in the manhole. A physical model investigation was performed under the same conditions as in the previous section.

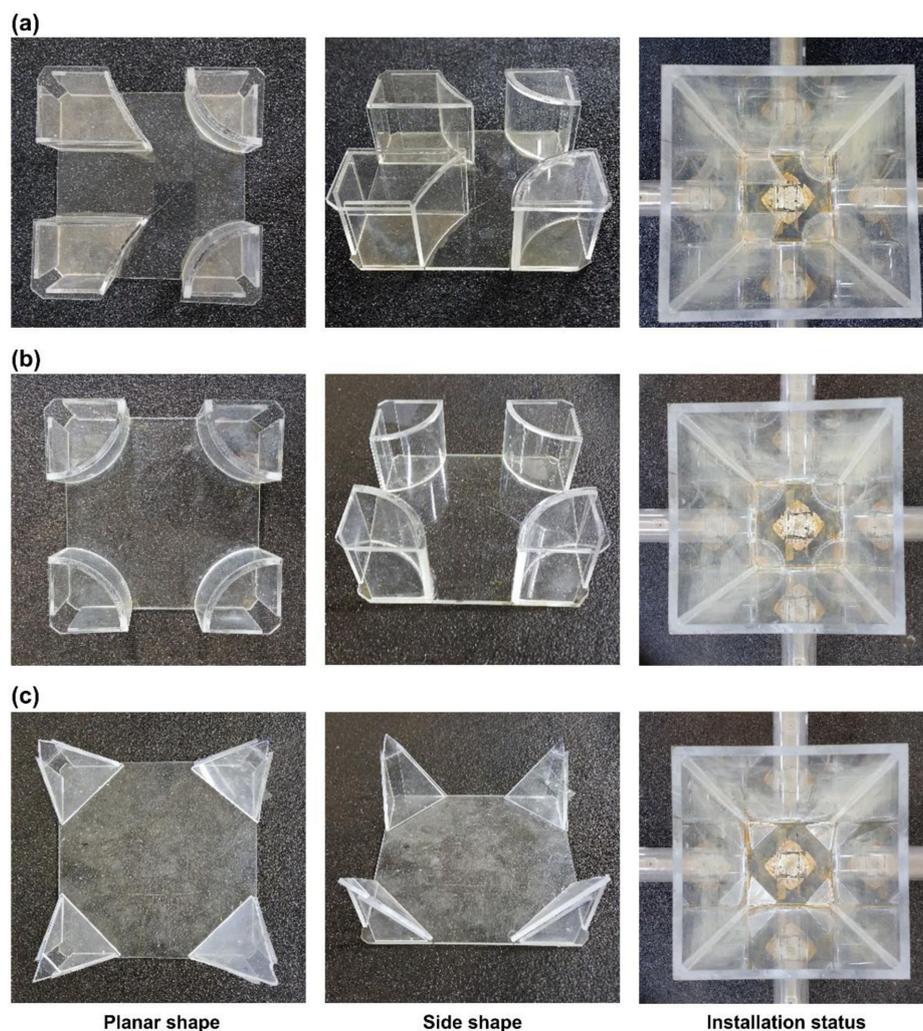


Figure 12. Benching models and installation diagrams: (a) Design 1; (b) Design 3; and (c) Design 4.

As in the previous section, substitution into Equation (6) was performed to calculate the head loss coefficient K in the surcharged four-way square junction manholes. Figure 13 shows the calculated head loss coefficient values with respect to the lateral flow rate ratio and the benching installation conditions. As shown in Figure 13, the head loss coefficient in the surcharged square manhole installed according to Designs 3 and 4 was approximately equal to the head loss coefficient in the surcharged square manhole without benching. As a result, benching installation according to Designs 3 and 4 had no significant effect on the head loss reduction and drainage capacity in the surcharged square manholes. The head loss coefficient in the surcharged square manhole installed according to Design 1 showed no significant effect on the head loss reduction when the lateral flow rate ratio was 0.25 or less. However, the head loss coefficient decreased by approximately 25–30% when the lateral flow rate ratio increased. Thus, benching installation according to Design 1 showed a significant head loss reduction and drainage capacity increase in the surcharged square manholes.

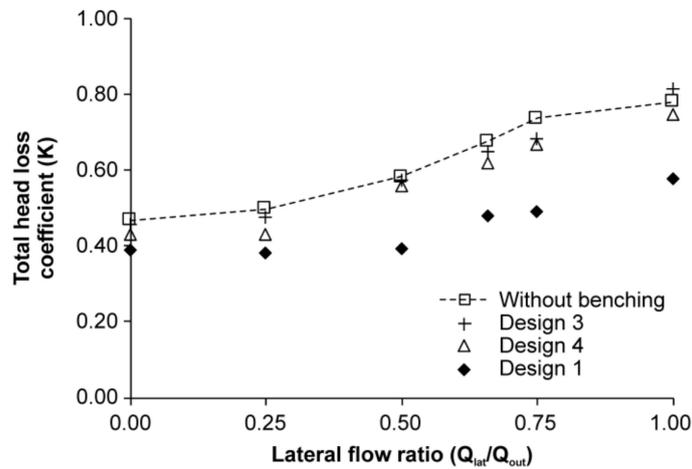


Figure 13. Change in the head loss coefficient of the square junction manhole considering the benching design.

3.2. Physical Model Investigation for Analyzing Head Loss Reduction by Rectangular Benching

Additional half benching was fabricated (i.e., 30 mm shorter than those in Figure 10) to analyze the change of head loss reduction in the square manhole caused by the benching floor configuration. Further physical model investigations were performed in the circular manholes by fabricating 60 mm (full rectangular) and 30 mm (half rectangular) benching according to Design 1 (Figure 14).

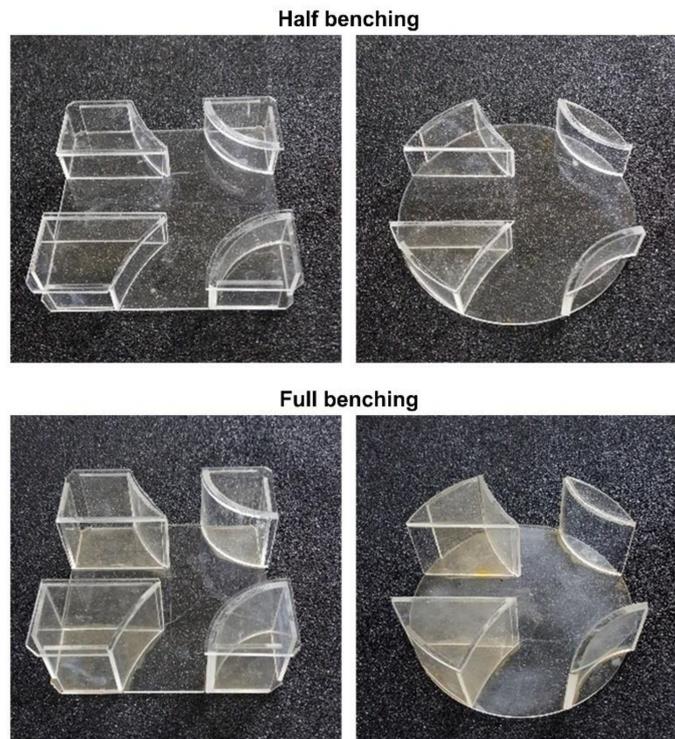


Figure 14. Production models for the rectangular benching.

The head loss reduction from the rectangular benching (Figure 14) was confirmed by calculating the head loss coefficients with respect to the changes from the same lateral influent flow rate ratios in the manhole without benching (Figure 15). The installation of the half rectangular benching reduced the head loss coefficients by 7% on average in square manholes and 10% on average in circular manholes. Moreover, the installation of the full rectangular benching reduced the head loss coefficients by 28%

on average in the square manholes and 17% on average in the circular manholes. Thus, a half or full rectangular benching can be installed depending on the conditions of the manhole to efficiently improve the drainage capacity of the surcharged four-way manholes.

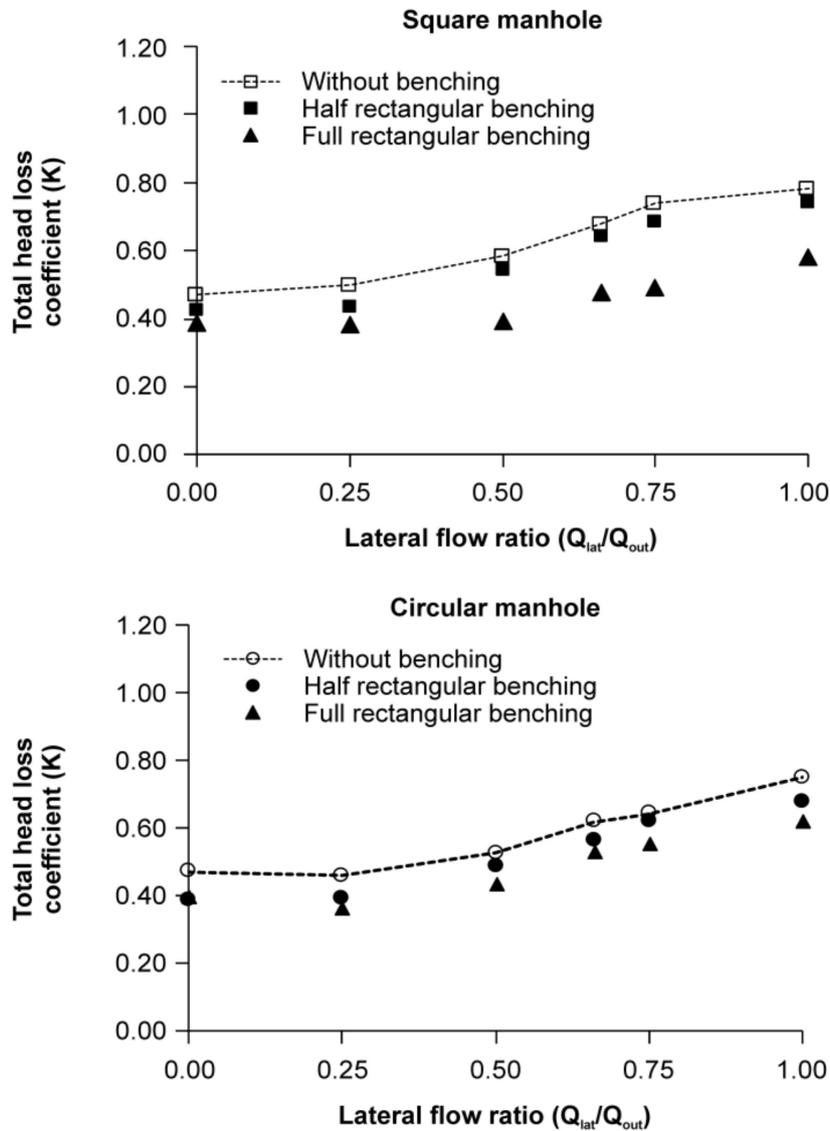


Figure 15. Change in the head loss coefficient of the four-way junction manhole with respect to the installation of rectangular benching.

4. Conclusions

This study aimed to analyze the applicability of the benching and derive the benching design that reduces the head loss and increases the drainage capacity of surcharged four-way junction manholes in an urban drainage system. Accordingly, 1/5 scale manholes and pipes were fabricated as the physical models to analyze the dependence of the head loss coefficients on the effluent flow rate, the benching floor configuration, and benching design. Numerical simulations were performed using the Fluent 6.3 model to analyze the flow pattern in the manhole and to derive the benching design. The following conclusions are drawn from this study:

1. The outflow reduction caused by the low-flow velocity sections at each corner of the manholes as well as the vortices in the vertical direction rising at the joint between the manhole and outflow pipes could be induced in the surcharged four-way manholes.

2. The installation of half and full rectangular benching reduced the head loss coefficients by 7% and 28% on average for square manholes and 10% and 17% on average for circular manholes, respectively.
3. The installation of the rectangular benching design decreased the head loss coefficients of the surcharged four-way manhole compared with those of the manhole without benching, thereby improving their drainage capacity. Hence, the rectangular benching design proposed herein could be installed and used to improve the drainage capacity of urban conduit facilities as they are designed and constructed.
4. The physical model investigation carried out in the study selected only five experimental flow rate ratios under restricted conditions in which the left and right inlet flow rates were the same in the four-way junction manhole. Further research is needed because the head loss coefficient at the surcharged four-way manhole diversely changes depending on the inflow rate conditions.

Author Contributions: Conceptualization, J.S.K. and S.E.Y.; Data curation, J.B.J. and J.S.K.; Formal analysis, J.B.J. and J.S.K.; Funding acquisition, S.E.Y.; Investigation, J.S.K. and J.B.J.; Methodology, J.S.K., J.B.J. and S.E.Y.; Project administration, J.S.K. and S.E.Y.; Resources, J.S.K. and S.E.Y.; Software, J.B.J. and J.S.K.; Supervision, S.E.Y.; Validation, J.S.K., J.B.J. and S.E.Y.; Visualization, J.S.K. and J.B.J.; Writing—original draft, J.S.K. and J.B.J.; Writing—review & editing, J.S.K. and J.B.J.

Funding: This research was funded by the Water Management Research Project grant number [17AWMP-B066744-05].

Acknowledgments: This research was supported by the Water Management Research Project funded by the Ministry of Land, Infrastructure and Transport (MOLIT) of the Korean government, grant number 17AWMP-B066744-05.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results

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