FORMULA ON ENERGY LOSSES AT THREE-WAY CIRCULAR DROP MANHOLE UNDER SURCHARGE FLOW

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Energy loss at manholes under surcharged conditions is as important as the friction loss in pipes in the design of storm sewer networks and in flood analysis. Some researchers have already proposed the formula to calculate the energy loss at three-way manholes under surcharged conditions. However, in most of these proposed formulas, all variables of structural elements for the pipes and the manholes have not been considered enough yet. Therefore, development of the formula to exactly calculate the energy loss at three-way manholes is needed. In this paper, the effect of diameter ratios between inflow pipes and an outflow pipe, the ratios of flow rates between inflow pipes, connected angles among those pipes and drop gaps between inflow pipes and outflow pipe on the energy loss at three-way circular drop manholes were investigated. Based on the experimental results, a new formula that considers all structural elements and the ratios of flow rates between inflow pipes was proposed for the energy loss coefficients at the manholes. In the proposed formula, calculated energy loss coefficients reproduce measured values more exactly than existing formulas do.

Key Words: connected pipe angle, drop manhole, formula on energy loss, urban storm drainage

1. INTRODUCTION

Inundation has been happening frequently because of an increase in localized torrential rainfall, and it has caused extensive damage in various places throughout the world in recent years. Not only countermeasures such as hardware, but also software are necessary to minimize damage based on appropriate refuge instruction measures by transmission of quick and correct weather information to inhabitants, flood hazard maps, and disaster prevention trainings. However, flood hazard maps that do not consider inundation due to interior runoff cannot determine expected inundation areas exactly and may cause difficulties in evacuating residents during inundation. To improve the reliability of the flood hazard map, it is necessary to evaluate the risk of flood quantitatively through accurate calculation of rainwater runoff and flow. Accurate calculation of the surface flow and precise indication of the places where water spills over through manholes of the storm sewer are inevitable to reduce risk. To do so, appropriate assessment on the discharge capacity of the storm sewer is needed. The discharge capacity of the storm sewer connected to manholes must be calculated by combining the frictional loss of the storm sewer and the head loss in the manhole. The head loss is not always smaller than that of the friction loss in the pipes1), 2), 3), 4). Flooding analysis software developed in foreign countries, such as XP-SWMM, InfoWorks, and MOUSE calculates the head loss at a manhole based on formulae that are different from each other. These formulae sometimes do not give an appropriate value to the head loss coefficient at manholes depending on the number of inflow pipes and junction conditions of the manhole and pipes. Moreover, the head loss coefficient at manholes is not included in most flood analysis models developed in Japan. Therefore a crucial problem has been left in the models on the analysis of inundation due
to interior runoff. The energy loss coefficient at a two-way circular drop manhole where an inflow pipe connects with an outflow pipe was already formulated by the authors\(^3\). Some formulae on energy loss at three-way manholes with two inflow pipes and one outflow pipe have been developed in some previous researches\(^3,4,5,6\). However, all constructional variables related to the manhole and the connecting pipes are not always considered, and the calculation formulae have a limitation on the applicable range. To calculate the energy loss at a manhole more accurately, it is necessary to develop a formula on the energy loss coefficient in which all constructional variables are considered.

In this study, energy losses at three-way circular drop manholes were investigated by conducting experiments with several kinds of pipe diameter, inflow flow rate, horizontal connecting angle between the inflow pipes and outflow pipe, and drop gap between those pipes. A formula on the energy loss that takes some hydraulic factors and all structural elements into account based on the experiment results was developed.

2. STRUCTURAL ELEMENTS AND VARIABLES TO BE CONSIDERED FOR FORMULATION OF ENERGY LOSS AT THREE-WAY MANHOLE

Structural elements related to energy loss at a three-way manhole are as follows:

1. Plane shape (square, rectangular and circular), bottom shape and diameter of the manhole,
2. Shape (circular and rectangular), diameter and slope of the pipes,
3. Vertical connection of pipes (crown alignment, center alignment, bottom alignment and drop connection), and
4. Horizontal connecting angle between inflow and outflow pipes.

Previous researches mainly targeted the bottom, crown and center alignments between the inflow and outflow pipes and research on the drop connection has been few.

The energy loss coefficient, \( K_e \), at a three-way circular drop manhole under surcharged flow is given in Equation (1) by a function of ten dimensionless variables and manhole bottom shape (refer to Fig. 1).

Under pressurized flow, Froude number \( V / \sqrt{gD} \) (\( V \) is the cross-sectional mean flow velocity; \( g \) is the gravitational acceleration; and \( D \) is the pipe diameter) can be neglected. In addition, it has been shown in previous studies\(^3,4,5\) that in the range of Reynolds number \(VD/\nu \) (\( \nu \) is dynamic viscosity of the fluid) of over 10000, the influence of Reynolds number can be neglected. In this study, these numbers are ignored.

\[
K_e = f \left( \frac{b}{D_1}, \frac{D_1}{D_2}, \frac{D_1}{D_3}, \frac{y}{D_1}, \frac{Q_i}{Q_{i1}} + \frac{Q_i}{Q_{i2}}, \frac{S_1}{S_2}, \frac{S_1}{S_3}, \frac{\theta_1}{180}, \frac{\theta_2}{180} \right) \tag{1}
\]

where \( b \) is the manhole diameter; \( D_i \) is the diameter of pipe \( i \); \( y \) is the water depth from the bottom of the manhole; \( Q_i \) is the flow rate of pipe \( i \) (\( Q_{i1} + Q_{i2} \)); \( S_i \) is the drop gap between inflow pipe \( i \) and outflow pipe; and \( \theta_i \) is the horizontal connecting angle between inflow pipe \( i \) and the outflow pipe.

Because pressurized flow is targeted in this study, the pipe slope is not included in Equation (1). Both pipe and manhole shapes are circular and they are not included as variables. The energy loss coefficient, \( K_{e*} \), and the pressure loss coefficient, \( K_{p*} \), at a three-way manhole are defined by Equations (2) and (3), respectively (refer to Fig. 2).

\[
K_{e*} = \frac{\Delta E}{V_1^2 / 2g} \tag{2}
\]

\[
K_{p*} = \frac{\Delta P}{V_2^2 / 2g} = K_{e*} + 1 - \left( \frac{V_2}{V_1} \right)^2 \tag{3}
\]

On the subscript * of \( K_{e*} \) and \( K_{p*} \), the subscript 1 shows the flow direction from inflow pipe 1 to the outflow pipe, and the subscript 2 shows the flow direction from inflow pipe 2 to the outflow pipe, where \( \Delta E* \) is the energy loss at the manhole; \( \Delta P* \) is
the pressure loss at the manhole; \( V^* \) is the cross-sectional mean flow velocity in the inflow pipe; \( V_3 \) is the cross-sectional mean flow velocity in the outflow pipe; and \( g \) is the gravitational acceleration.

3. PREVIOUS RESEARCH ON ENERGY LOSS AND PRESSURE LOSS AT MANHOLES

In a previous research, the energy loss coefficient at a two-way circular manhole under surcharged flow has been formulated by the authors. Researches on energy loss at a three-way manhole have been conducted by Marsalek, Lindvall, Sangster et al., Johnston & Volker, Townsend & Prins, FHWA, and the authors. Most of these researches are for steady flow and pressurized flow, and research considering the drop gap between the inflow pipe and the outflow pipe has been few. In most researches, one horizontal connecting angle between the inflow and outflow pipes is 180° and the other connecting pipe angle is 90°. Research of other than 90° has been done only by Townsend & Prins, Marsalek, Lindvall, Sangster et al., and the authors. Marsalek indicated that the theoretical formula is able to applicable when the water depth in a manhole is large enough, because the influence of the water depth is not considered.

\[
K_{P1} = 0.27 - 0.095 \frac{b}{D_1} \\
+ \left( 1.1 + 0.09 \frac{b}{D_1} \right) \frac{Q_2}{Q_3} \left( \frac{D_1}{D_3} \right)^{1.8} \times \left( \frac{D_1}{D_3} \right)^{-a_1} \tag{4}
\]
\[
a_1 = 2.0 - 0.22 \frac{b}{D_1} \tag{5}
\]

However, the influence of water depth, \( y \), in a manhole was not considered in the equation proposed by Lindvall, and thus a problem remains.

Sangster et al. indicated that the flow rate ratio, \( Q_2/Q_3 \), between the lateral pipe (\( \theta=90° \)) and the outflow pipe and the diameter ratio, \( b/D_3 \) between the manhole and the outflow pipe influenced energy loss at the manhole. Moreover, Sangster et al. led an equation that theoretically Sangster et al. calculated the pressure loss coefficient for the main straight-through pipe (\( \theta=180° \)) and the lateral pipe (\( \theta=90° \)) from the continuity equation and the momentum conservation equation at the entrance and the exit of the manhole. The pressure loss coefficients, \( K_{P1} \) for the main straight-through pipe and \( K_{P2} \) for the lateral pipe are given in the following equations:

\[
K_{P1} = \overline{K_{P1}} \times K_{P1}' \tag{8}
\]
\[
K_{P1}' = 1 - \left( \frac{Q_2}{Q_3} \times \left( \frac{D_1}{D_3} \right) \right)^2 \tag{9}
\]
\[
K_{P2} = \overline{K_{P2}} \times K_{P2}' \tag{10}
\]
\[
K_{P2}' = 1 - \left( \frac{Q_2}{Q_3} \times \left( \frac{D_1}{D_3} \right) \right)^{2.0/a_1} \tag{11}
\]

where \( Q_1 \) is the flow rate of the main straight-through pipe, \( Q_2 \) is the flow rate of the lateral pipe, \( Q_3 \) is the flow rate of the outflow pipe, \( D_1 \) and \( D_2 \) are the diameters of the inflow pipes, and \( D_3 \) is the diameter of the outflow pipe. \( \overline{K_{P1}} \) and \( \overline{K_{P2}} \) show the correction factors on pressure loss based on experimental results obtained by changing \( b/D_3 \) and \( D_3/D_2 \).

Sangster et al. indicated that the theoretical values agreed with the experimental values as far as the manhole diameter was considerably large compared with the outflow pipe diameter and the diameter of the main straight-through pipe was equal to that of the lateral pipe. However, these equations seem applicable when the water depth in a manhole is large enough, because the influence of the water depth is not considered.

Johnston & Volker formulated a relationship be-
between the pressure loss coefficient and the flow rate ratio for the main straight-through pipe and the lateral pipe based on the experimental results as follows:

\[
K_{p1} = -3.26 + 11.0 \left( \frac{Q_i}{Q} \right) - 5.74 \left( \frac{Q_i}{Q} \right)^2 - 0.05 \left( \frac{Q_i}{Q} \right)^3 \quad (12)
\]

\[
K_{p2} = -2.99 + 10.78 \left( \frac{Q_i}{Q} \right) - 6.60 \left( \frac{Q_i}{Q} \right)^2 + 0.71 \left( \frac{Q_i}{Q} \right)^3 \quad (13)
\]

However, these are estimated equations based on experimental results, which were obtained under fixed diameter ratio (the outflow pipe diameter was larger than the inflow pipe diameter), and are not applicable under conditions different from the experiments. The influence of water depth in the manhole was also not considered in the equations.

FHWA has published Urban Drainage Design Manual (UDDM) on the internet. (http://www.fhwa.dot.gov/bridge/hec22.pdf). The equations in the manual seem to be the widest range of application on the energy loss at three-way manhole. The calculation formulae are shown below:

\[
K_e = K_0 C_D C_d C_Q C_r C_B
\]

\[
K_0 = 0.1 \left( \frac{b}{D_i} \right) \left( 1 - \sin \theta_i \right) + 1.4 \left( \frac{b}{D_i} \right)^{0.15} \sin \theta_i \quad (14)
\]

\[
C_D = \left( \frac{D_i}{D_j} \right)^3 \quad (15)
\]

\[
C_d = 0.5 \left( \frac{y}{D_i} \right)^{0.6} \quad (16)
\]

\[
0 \leq \frac{y}{D_i} \leq 3.2 \text{, } \frac{y}{D_i} > 3.2 \text{ then } C_d = \frac{1}{K_0}
\]

\[
C_Q = \left( 1 - 2 \sin \theta_i \right) \left( 1 - \frac{Q_i}{Q} \right)^{0.75} + 1 \quad (17)
\]

\[
C_r = 1 + 0.2 \left( \frac{z}{D_i} \right) \left( \frac{y}{D_i} \right) \quad (18)
\]

where \(D_i\) is the diameter of inflow pipe \(i\); \(D_j\) is the diameter of the outflow pipe; \(b\) is the manhole diameter; \(\theta_i\) is the horizontal angle between inflow pipe \(i\) and the outflow pipe; \(K_0\) is the coefficient for \(b/D_i\) and \(\theta_i\); \(C_D\) is the coefficient for \(D_i/D_j\); \(y\) is the water depth in the manhole; \(C_d\) is the coefficient for \(y/D_i\); \(C_Q\) is 1 (surcharge flow for \(y/D_i > 3.2\)); \(Q_i\) is the flow rate of inflow pipe \(i\); \(Q\) is the outflow flow rate; \(C_Q\) is the coefficient for \(Q_i/Q\); \(C_r\) is the coefficient for plunging flow; \(C_r = 1\) (no effect of plunging flow); \(z\) is the vertical distance of plunging flow from the flow line of the higher elevation inflow pipe to the center of the outflow pipe; and \(C_B\) is the coefficient for manhole bottom shape; \(C_B = 0.95\) (half benching).

The equations described in UDDM assume the pipe shape and manhole shape to be circular and include all structural variables except the drop gap between the inflow and outflow pipes in the variables of Equation (1). In the authors’ research for Equations (14)−(19), however, it was confirmed that there was a difference between the calculated results and the experimental results according to the combination of the pipe diameter and the flow rate ratio, and a problem remains on the application of the equations in UDDM (refer to Figs. 7 and 8).

The authors have developed the formula for energy loss at the manhole in which the drop gap was considered between the straight-through pipe or the lateral pipe and the outflow pipe. However, only the horizontal connecting angle of the lateral pipe is changeable in this calculation formula. In addition, in the authors’ research, a calculation formula that considered the change in connecting angle of two inflow pipes in which there was no drop gap between the inflow and outflow pipes was proposed; however, there was a problem in the expression form. Therefore, an appropriate value might not be obtained as an energy loss coefficient depending on the sizes of manhole diameter and connecting pipe diameter, and the authors have realized the need to revise the expressions. As mentioned above, all structural variables related to the manhole and the connecting pipe are not always considered in these formulae, and there is a limitation within the range of the application of the formula. Because many hydraulic factors and structural elements to be examined exist on the connecting pipe and the manhole, problems regarding the application of these formulae still exist. Moreover, though there are some experimental studies considering the drop gap between those pipes under pressurized pipe flow, there have been few research to formulate the loss coefficient considering the drop gap under T intersection. In this study, a formula for the energy loss with all structural variables including the drop gap between the inflow and outflow pipes is developed.

4. EXPERIMENTAL APPARATUS AND PROCEDURE

(1) Experimental apparatus
The outline of the experimental apparatus used in this study is shown in Figs. 3 and 4. The manhole and the pipe are made of transparent acrylic resin. Figure 3 shows the horizontal connecting angles between the inflow pipes and outflow pipe as \(\theta_1 = 180^\circ\) and \(\theta_2 = 90^\circ\). Figure 4 shows those angles with opposed inflow pipes as \(\theta_1 = 90^\circ\) and \(\theta_2 = 90^\circ\).

The experimental model is a scale of 1/5 of real scale (manhole diameter is 90cm and pipe diameter
is 25cm), and manhole shape as a form of cylinder is simpler than the prototype. The invert corresponding to 1/2 of the pipe diameter generally used in Japan is set up in the manhole bottom.

(2) Experimental procedure
1) Flow in the pipes is regulated pressurized flow by two flow rate control valves, and $Q_1$ and $Q_2$ are set to prescribed flow rates. The measurement accuracy of the flow rate has a range of error within ±1%.

2) The distance from the inside wall top of the higher elevation inflow pipe to the water surface is the water depth $h$ in the manhole. The water depth $h$ in the manhole is adjusted by the weir in the overflow tank at the end of the outflow pipe.

3) The water depth $h$ in the manhole is measured by scales installed at four points along the wall outside the manhole. The value of $h$ is an averaged value of those. When $h$ is 5cm in the manhole with two opposed inflow pipes (each pipe diameter is 5cm), water surface in the manhole intensely fluctuates up and down, and the maximum fluctuation of water surface is around ± 15mm. The fluctuation of water surface becomes small as $h$ in the manhole increases.

The fluctuation of water surface becomes about ±2.5mm when $h$=10cm and becomes about ±0.5mm when $h$=20cm.

4) The pressure heads of the pipes are measured twice with manometers installed in inflow pipes 1 and 2 and the outflow pipe, respectively, at three places. The energy loss, $\Delta E$, at the manhole is obtained by calculated energy grade line based on the measured pressure head and velocity head ($V^2/2g$) (refer to Fig. 2). In addition, the energy loss coefficient $K_{e*}$ is calculated by Equation (2) and the pressure loss coefficient $K_{p*}$ is calculated by Equation (3). The mean value of the energy loss coefficients is adopted when the water depth ratio $h/D_3$ in each flow rate ratio is larger than 2. As described later, in this study, when the energy loss at a three-way circular drop manhole under surcharged flow is formulated, the influence of water depth in the manhole is not considered.

(3) Experimental conditions
Including the previous research, the combination for the pipe diameter ($D_1$, $D_2$ and $D_3$), the horizontal connecting angle ($\theta_1$ and $\theta_2$) between the inflow and the outflow pipes and the drop gap ($S_1$ and $S_2$) between those pipes is indicated in Table 1.

![Fig. 3](image-url) Experimental apparatus ($\theta_1=180^\circ$ and $\theta_2=90^\circ$).

![Fig. 4](image-url) Two opposed inflow pipes ($\theta_1=90^\circ$ and $\theta_2=90^\circ$).

Table 1 Combination of pipe diameter, horizontal connecting angle and drop gap between inflow and outflow pipes.

| $\theta_1$ | $\theta_2$ | $D_1$ | $D_2$ | $D_3$ | $S_1$ | $S_2$ |
|---|---|---|---|---|---|---|
| Type A | $180^\circ$ | 5cm | 5cm | 5cm | 0cm 5cm 5cm 2.5cm 5cm |
| Type B | 5cm | 5cm | 6cm | Center alignment |
| Type C | 5cm | 4cm | 6cm | 1cm 6cm 11cm 2cm 7cm 12cm |
| Type D | 4cm | 5cm | 6cm | 2cm 7cm 12cm 1cm 6cm 11cm |
| Type E | 5cm | 3cm | 6cm |
| Type F | 3cm | 5cm | 6cm |
| Type G | 3cm | 3cm | 6cm |
| Type H | $90^\circ$ | 5cm | 5cm | 6cm |
| Type I | 5cm | 3cm | 6cm |
| Type J | 3cm | 5cm | 6cm |
| Type K | 3cm | 3cm | 6cm |

Types A–G

Types H–K

Crown alignment
The flow rates $Q_1$ and $Q_2$ were changed as shown in Table 2, and nine kinds of flow rate ratios $Q_2/Q_3$ ($Q_3 = Q_1 + Q_2$), were set. The water depth $h$ in the manhole was changed in the range from 1 to 30 cm by each flow rate ratio.

5. EXPERIMENTAL RESULTS AND DISCUSSION

(1) Influence of water depth ratio

For $Q_2/Q_3 = 0.0, 0.5$ and $1.0$, the relationships between the energy loss coefficient, $K_{e1}$ or $K_{e2}$ and the water depth ratio, $h/D_3$ in the manhole are shown in Figs. 5 and 6. The numerical value in parentheses such as Type A (5-5-5) in the explanatory notes in those figures shows the diameter (cm) of inflow pipe 1, inflow pipe 2 and the outflow pipe from the left. The plotted data in those figures indicate the measured values, and the lines indicate the calculated results in figures mentioned after. Types B and G are for $\theta_1 = 180^\circ$ and $\theta_2 = 90^\circ$, and Types H and K are for $\theta_1 = 90^\circ$ and $\theta_2 = 90^\circ$. For $Q_2/Q_3 = 0$ and $h/D_3 = 0.1–0.5$, if Type B is compared with Type H ($D_1 = D_2 = 5$cm and $D_3 = 6$cm), $K_{e1}$ or $K_{e2}$ in each type becomes the same value, respectively, for the following reason:

The influence of changes in the connecting angle of inflow pipe 1 from $180^\circ$ (Type B) into $90^\circ$ (Type H) is small, and water flows in only straight-through pipe in Type B. A horizontal swirling motion that separates in the direction of flow right and left or a horizontal rotational motion in a single direction occurs as the water depth ratio $h/D_3$, in the manhole increases up to about 0.6, and the energy loss at the manhole increases. When the water depth ratio increases beyond about 0.5, a large-scale swirling motion disappears in Types B and G ($\theta_1 = 180^\circ$), and the loss coefficient decreases. When the flow rate ratio $Q_2/Q_3$ is 0.5, $K_{e1}$ or $K_{e2}$ in both Type B and Type H almost the same value and $K_{e1}$ or $K_{e2}$ in both Type G and Type K has also almost the same value.

For $Q_2/Q_3 = 0.5$, the influents from inflow pipe 1 and pipe 2 collide mutually in the manhole, therefore the energy loss increases; on the other hand, the influence of the horizontal connecting angle between the inflow and outflow pipes becomes small.

![Fig. 5](image1.png) **Fig. 5** Relationship between $K_{e1}$ and $h/D_3$ (Without drop gap between inflow and outflow pipes).

![Fig. 6](image2.png) **Fig. 6** Relationship between $K_{e2}$ and $h/D_3$ (Without drop gap between inflow and outflow pipes).

| Table 2 Experimental flow rate ratio, $Q_2/Q_3$. |
|-----------------------------------------------|
| ![Table 2](image3.png)                       |

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Moreover, at this flowrate ratio, the energy loss coefficient does not depend on water depth in the manhole, and it almost becomes constant. For \( Q_2/Q_3 = 1.0 \) and \( h/D_3 < 0.5 \), \( K_{e1} \) in all Types keeps almost the same value. As mentioned above, this is because the influence of the swirling motion in the manhole becomes predominant as the water depth in the manhole decreases. In addition, \( K_{e2} \) has almost the same value, if the combination of the pipe diameter is of the same type. The reason is that when \( Q_2/Q_3 = 1.0 \), water does not flow in inflow pipe 1, and therefore even if the connecting pipe angle is changed, \( K_{e2} \) is not influenced by inflow pipe 1. When \( h/D_3 > 2.0 \) in each flow rate ratio, the influence of water depth in the manhole is small, and \( K_{e1} \) and \( K_{e2} \) become almost a constant value, respectively. From the above-mentioned, the energy loss coefficient in each flow rate ratio was adopted to be a mean value for \( h/D_3 > 2.0 \).

(2) Influence of pipe diameter ratio and flow rate ratio \((\theta_1=180^\circ \text{ and } \theta_2=90^\circ)\)

The relationship between the energy loss coefficient, \( K_{e1} \) of inflow pipe 1 \((\theta_1=180^\circ)\) and the flow rate ratio \( Q_2/Q_3 \) is shown in Fig. 7. When Type B \((D_3/D_1 = D_3/D_2 = 1.2)\) is compared with Type C \((D_3/D_1 = 1.2, D_3/D_2 = 1.5)\), the energy loss coefficient \( K_{e1} \) of Type C becomes large in the range of 0.3-0.7 of \( Q_2/Q_3 \). This is because the flow velocity from inflow pipe 2 to the manhole increases by reducing diameter \( D_2 \) of the pipe from 5cm to 4cm, and therefore the influence of collision of the influent from inflow pipes 1 and 2 in the manhole increases. The energy loss coefficient increases because water in inflow pipe 1 cannot smoothly flow to the outflow pipe by collision of the influent from inflow pipes 1 and 2. When \( Q_2/Q_3 \) is 0, the energy loss coefficient in both types becomes almost the same because water does not flow in inflow pipe 2, and the difference of \( D_2 \) of inflow pipe 2 does not influence the energy loss of inflow pipe 1. When Type B is compared with Type D \((D_3/D_1 = 1.5, D_3/D_2 = 1.2)\), the energy loss coefficient \( K_{e1} \) of Type D becomes large in the range of about 0.0-0.8 of \( Q_2/Q_3 \). The reason is that the flow velocity from inflow pipe 1 to the manhole increases by reducing diameter \( D_1 \) of the pipe from 5cm to 4cm, and therefore the influence of collision of part of slightly expanding flow from inflow pipe 1 into the side wall of the manhole exit increases and the energy loss becomes larger. The comparison with the calculated values by UDDM is shown in Fig. 7. The calculated values by the equations described in UDDM are fairly different from the measured values in some cases of the combination of the diameter ratio between the inflow and the outflow pipes. Especially, Type D is different from other types, the relationship between the flow rate ratio and the loss coefficient shows an opposite tendency, and the measured value in Type D is not expressed by the formula in UDDM at all. In addition, there is a fatal problem in that the change in the diameter of inflow pipe 2 is not considered by the formula of UDDM.

The energy loss coefficient \( K_{e2} \) of inflow pipe 2 \((\theta_2=90^\circ)\) is a function of the flow rate ratio \( Q_2/Q_3 \) as shown in Fig. 8. In each type, the energy loss coefficient \( K_{e2} \) takes the maximum value at \( Q_2/Q_3 = 1.0 \), and it becomes the minimum at \( Q_2/Q_3 = 0 \). \( Q_2 \) of inflow pipe 2 increases compared with \( Q_1 \) of inflow pipe 1 when \( Q_2/Q_3 > 0.5 \). Therefore, the influence of influent from inflow pipe 1 becomes small, and flowing water from inflow pipe 2 collides directly with the side wall of the manhole. When \( Q_2/Q_3 > 0.7 \), the energy loss coefficient \( K_{e2} \) increases because the energy that corresponds to the velocity head is lost. As for Type C \((D_3 = 4cm)\), because the inflow velocity increases and the influence of the collision becomes larger when the diameter of inflow pipe 2 becomes small, the energy loss coeffi-
cient increases compared with other Types. When $Q_2/Q_3 < 0.5$, $Q_1$ of inflow pipe 1 increases compared with $Q_2$ of inflow pipe 2 and therefore, the influent from inflow pipe 2 flows easily as it is pushed by the influent of inflow pipe 1, and the energy loss coefficient $K_{e1}$ becomes small. The energy loss coefficient in Type D ($D_1=4$cm) becomes small compared with other types, so that water may flow more smoothly in the manhole as diameter $D_1$ of inflow pipe 1 becomes smaller. For $Q_2/Q_3=0.0−0.2$, the energy loss coefficient $K_{e2}$ becomes a negative value. In the range of this flow rate ratio, influent from inflow pipe 1 flows to the manhole without being interrupted by influent from inflow pipe 2, and water mightily flows into the outflow pipe. Therefore, the pressure head in the manhole decreases based on Bernoulli’s theory and the water level in the manhole decreases. The pressure head of inflow pipe 2 is lowered more than the energy head of water of the outflow pipe because the water level in the manhole decreases, thus for $Q_2/Q_3=0.0−0.2$, the energy loss coefficient $K_{e2}$ becomes a negative value. Because the diameter of inflow pipe 1 of Type D is smaller than that of other types, the flowing velocity from inflow pipe 1 into the manhole of Type D increases, and a negative value of the energy loss coefficient $K_{e2}$ becomes larger. The comparison with the calculated values by UDDM is shown in Fig. 8. The formula described in UDDM is faulty in that the energy loss coefficient $K_{e2}$ always becomes 0 in any case when the horizontal connecting pipe angle $\theta$ is 90° and $Q_2/Q_3=0$.

(3) Influence of horizontal connecting angle $\theta$ between inflow and outflow pipes

When the horizontal connecting angle between the inflow pipe and the outflow pipe is changed, the relationships between the energy loss coefficients $K_{e1}$ and $K_{e2}$ and the flow rate ratio $Q_2/Q_3$ are shown in Figs. 9 and 10 (refer to Figs. 11 and 12). Types B, E, F, and G are for $\theta_1=180°$ and $\theta_2=90°$, and Type H, I, J, and K are for $\theta_1=90°$ and $\theta_2=90°$. The energy loss coefficient $K_{e1}$ for inflow pipe 1 as shown in Fig. 9, indicates almost the same value even if the horizontal connecting angle $\theta_1$ for inflow pipe 1 is changed from 180° to 90° when $Q_2/Q_3$ is about 0.5 and the combination of the pipe diameter is the same (for instance, Type B and Type H, Type E and Type I). In other flow rate ratios, the energy loss coefficient $K_{e1}$ of Types I and K ($\theta_1=90°$ and $\theta_2=90°$) in which the diameter $D_2$ (=3cm) of inflow pipe 2 is smaller, is larger than that of Types E and G ($\theta_1=180°$ and $\theta_2=90°$). When $Q_2/Q_3<0.5$ and the horizontal connecting angle $\theta_1$ for inflow pipe 1 is adjusted to 90° like Types H–K, the influence of the bending at the manhole bottom increases. Therefore, influent from inflow pipe 1 has difficulty flowing to the outflow pipe unlike in the cases of Type B and Types E–G ($\theta_1=180°$), and $K_{e1}$ for Types H–K increases. Especially, for Types J and K ($\theta_1=90°$), the diameter $D_1$ (=3cm) of inflow pipe 1 is small, the flow velocity is large, and the influence of the bending at the manhole increases. Therefore, the energy loss coefficient of Types J and K fairly increases more than that of Types F and G ($\theta_1=180°$). When $Q_2/Q_3>0.5$, $Q_2$ of inflow pipe 2 increases more than $Q_1$ of inflow pipe 1. Especially, when the two inflow pipes are opposed like Types I and K with small diameter $D_1$ (=3cm) of inflow pipe 2, the flow velocity of inflow pipe 2 becomes large and influent from inflow pipe 2 influences inflow pipe 1 more greatly. Therefore, the pressure head in inflow pipe 1 increases and $K_{e1}$ increases more than that in the case of $\theta_1=180°$. As shown in Fig. 10, the energy loss coefficient $K_{e2}$ of Types H–K ($\theta_1=90°$ and $\theta_2=90°$) is larger than that of Type B and Types
E−G ($\theta_1=180^\circ$ and $\theta_2=90^\circ$) when $Q_2/Q_1 < 0.5$ and the combination of the pipe diameter is the same. As mentioned above, when $Q_2/Q_1 < 0.5$, at the manhole with two opposed inflow pipes such as Types H−K, because pressure head in inflow pipe 2 increases due to the influence of influent of inflow pipe 1, the energy loss at the manhole increases. Especially, for Types J and K ($\theta_1=90^\circ$), diameter $D_1 (=3cm)$ of inflow pipe 1 is small and the flow velocity is large, and therefore the influence to inflow pipe 2 increases and this tendency becomes remarkable. When $Q_2/Q_1 > 0.5$ and the combination of the pipe diameter is the same, even if the connecting angle $\theta_1$ for inflow pipe 1 is changed from $180^\circ$ into $90^\circ$, $K_{e2}$ becomes almost the same value. The reason is that at $Q_2/Q_1 > 0.5$, the influence of inflow pipe 1 becomes small, and the influence of bending of influent from inflow pipe 2 in the manhole becomes predominant. The difference is not in $K_{e2}$ when the influence of inflow pipe 2 is predominant, because the horizontal connecting angle of inflow pipe 2 is $90^\circ$ in all Types.

(4) Influence of the drop gap between of inflow and outflow pipes ($\theta_1=180^\circ$ and $\theta_2=90^\circ$)

For Types A, C and D ($\theta_1=180^\circ$ and $\theta_2=90^\circ$), the relationship between $Q_2/Q_1$ and the energy loss coefficient at the manhole with the drop gap $S_1$ between inflow pipes 1 and the outflow pipe, and $S_2$ between inflow pipes 2 and the outflow pipe is shown in Figs. 15–20 (refer to Figs. 13 and 14).

a) Energy loss coefficient $K_{e1}$ for inflow pipe 1

The relationship between the energy loss coefficient $K_{e1}$ of inflow pipe 1 in Types A, C, and D and $Q_2/Q_1$ is indicated in Figs. 15–17, respectively. First, when the influence of the drop gap $S_1$ between inflow pipe 1 and the outflow pipe is examined in the case of $[S_1=0 cm$ and $S_2=0 cm]$ and $[S_1=5 cm$ and $S_2=0 cm]$, for $Q_2/Q_1 \leq 0.5$, the energy loss coefficient of the latter is larger as indicated in Fig. 15. This is because influent from inflow pipe 1 collides with the inside wall of the manhole exit and is not able to flow directly to the outflow pipe by drop gap $S_1 (=5cm)$ for inflow pipe 1 (refer to Fig.13). The energy that corresponds to the velocity head by the collision of this influent to the manhole exit is lost, and the energy loss coefficient increases. When $Q_2/Q_1 > 0.5$, the energy loss coefficient of each case becomes almost the same value. This is because the flow rate of inflow pipe 1 decreases compared with the flow rate of inflow pipe 2 and the influence of the influent from inflow pipe 2 increases more than the influence of the drop gap $S_1$ for inflow pipe 1. Second, when the influence of the drop gap $S_2$ between inflow pipe 2 and the outflow pipe is examined in the case of $[S_1=5 cm$ and $S_2=0 cm]$ and $[S_1=5 cm$ and $S_2=5 cm]$, the energy loss coefficient of both cases is the same as indicated in Fig. 15. The reason is that the influent from inflow pipe 2 collides with the side wall of the manhole regardless of the presence of the drop gap $S_2$. As shown in Fig. 17, even if the cases of $[S_1=12 cm$ and $S_2=1 cm]$ and $[S_1=12 cm$ and $S_2=11 cm]$ are compared, a similar tendency is obtained. Therefore, it is understood that the drop gap $S_2$ for inflow pipe 2 hardly influences the energy loss coefficient $K_{e1}$ for inflow pipe 1. In addition, as shown in Fig. 16, if the energy loss coefficients in the cases of $[S_1=6 cm$ and $S_2=7 cm]$ and $[S_1=11 cm$ and $S_2=12 cm]$ are compared, the energy loss coefficient of the latter is slightly larger in some flow rate ratios. If the cases of $[S_1=7 cm$ and $S_2=6 cm]$ and $[S_1=12 cm$ and $S_2=11 cm]$ are compared as shown in Fig. 17, a comparable result is obtained. Therefore, when the drop for inflow pipes 1 and 2 becomes a size larger than the diameter of the outflow pipe, the influence that the difference of the drop gives to the energy loss coefficient for inflow pipe 1 is very small.

b) Energy loss coefficient $K_{e2}$ for inflow pipe 2

The relationship between the energy loss coefficient $K_{e2}$ for inflow pipe 2 in Types A, C and D and
Fig. 14 Manhole and pipes (With drop gap between inflow and outflow pipes).

Fig. 15 Influence of drop gap (Type A, $K_{e1}$).

Fig. 16 Influence of drop gap (Type C, $K_{e1}$).

Fig. 17 Influence of drop gap (Type D, $K_{e1}$).

Fig. 18 Influence of drop gap (Type A, $K_{e2}$).

Fig. 19 Influence of drop gap (Type C, $K_{e2}$).

Fig. 20 Influence of drop gap (Type D, $K_{e2}$).
the flow rate ratio, \( Q_2/Q_1 \) is shown in Figs. 18–20 respectively. As shown in Fig. 18, when the energy loss coefficient in the cases of \([S_1]=0 \text{ cm and } S_2=0 \text{ cm}\) and \([S_1]=5 \text{ cm and } S_2=0 \text{ cm}\) are compared, the energy loss coefficient of the latter increases for \( Q_2/Q_1 \leq 0.5 \) as well as the energy loss coefficient \( K_{e1} \) for inflow pipe 1. This is because influent from inflow pipe 1 collides with the inside wall of the manhole exit and is not able to flow directly to the outflow pipe by drop \( S_1 \) (=5cm) for inflow pipe 1 as mentioned above. As a result, the pressure head in the manhole increases, and the water level in the manhole rises. Therefore, the pressure head in inflow pipe 2 increases and the energy loss coefficient \( K_{e2} \) increases. For \( Q_2/Q_1 >0.5 \), the energy loss coefficients in both cases of \([S_1]=0 \text{ cm and } S_2=0 \text{ cm}\) and \([S_1]=5 \text{ cm and } S_2=0 \text{ cm}\) become almost the same. The reason is that the flow rate of inflow pipe 1 decreases compared with the flow rate of inflow pipe 2, and the influence of collision of influent from inflow pipe 2 to the side wall of manhole is larger than the influence of the drop gap \( S_1 \) for inflow pipe 1, as mentioned above. It is understood that the influence that the drop gap \( S_1 \) for inflow pipe 1 gives to the energy loss coefficient \( K_{e2} \) for inflow pipe 2 increases when \( Q_2/Q_1 \leq 0.5 \).

Also, when the influence of the drop gap \( S_2 \) between inflow pipe 2 and the outflow pipe is examined in the cases of \([S_1]=5 \text{ cm and } S_2=0 \text{ cm}\) and \([S_1]=5 \text{ cm and } S_2=5 \text{ cm}\), the energy loss coefficient of both cases is the same as indicated in Fig. 18. As shown in Fig. 20, if the energy loss coefficients in the cases of \([S_1]=12 \text{ cm and } S_2=1 \text{ cm}\) and \([S_1]=12 \text{ cm and } S_2=11 \text{ cm}\) are compared, the energy loss coefficient of the latter is slightly larger. As a result, it is understood that the influence that drop \( S_2 \) for inflow pipe 2 gives to the energy loss coefficient \( K_{e2} \) is small. The reason is that influent from inflow pipe 2 collides with the side wall of the manhole regardless of the presence of the drop \( S_2 \) for inflow pipe 2. As shown in Fig. 19, if the energy loss coefficients \( K_{e2} \) in the cases of \([S_1]=6 \text{ cm and } S_2=7 \text{ cm}\) and \([S_1]=11 \text{ cm and } S_2=12 \text{ cm}\) are compared, the energy loss coefficient of the latter is slightly larger similar to that of \( K_{e1} \). When the drops for inflow pipes 1 and 2 become larger than the diameter of the outflow pipe, the influence that the difference in the size of the drop gives to the energy loss coefficient for inflow pipe 2 is very small.

6. FORMULATION OF ENERGY LOSS COEFFICIENT

(1) Theory of formulation

In this study, the energy loss coefficient at three-way circular drop manholes is formulated based on the formula described in UDDM as mentioned before in Chapter 3. In previous researches for calculation of the energy loss coefficient \( K_{e1} \), the applicable range of the equations in UDDM is wide.

(2) Formulation

In order to obtain accurate values, Equations (20)–(33) are proposed as new calculation formulae for the energy loss coefficient at the manhole based on the results of previous researches and experimental results of this study. The functional types of these Equations were decided to be able to express the experimental results adding the examination to various coefficients and multipliers of Equations (20)–(33). First, for the formulation, the coefficients and the multipliers in Equations (21)–(23) were decided to be able to express the measured values of Type A in which the diameter ratio between the outflow pipe and the inflow pipe was 1.0. In this formulation, the values of \( C_{Dh}, C_{Dj}, C_{Si} \) and \( C_{Sj} \) in Equations (24)–(27) are 0. Second, to express the influence by the difference of the pipe diameter ratio, the coefficients and the multipliers in Equations (24)–(27) were decided based on the measured values of Types B–G. The multiplier related to the flow rate ratio decides the shape of the function curve to express the experimental data, and the coefficient \( \alpha \) decides the scale of the curve. In addition, the multipliers, the terms of \( \left\{ \left( \frac{Q_2}{Q_1} \right)^4 - 1 \right\} \) and \( \left\{ \left( \frac{Q_2}{Q_1} \right)^4 - 1 \right\} \), were determined to be able to express the effect of the difference in the pipe diameter ratio, at \( Q_1/Q_3 = 1 \) or \( Q_1/Q_3 = 0 \). At the manholes with no drop gaps between the inflow and outflow pipes (crown alignment), the proposed formula is applicable to the range of \( 90° \leq \theta_1, \theta_2 \leq 180° \). At the manholes with drop gaps between those pipes, the proposed formula is applicable to \( \theta = 180° \) (fixed) and the range of \( 90° \leq \theta < 180° \) as another connecting angle between those pipes (refer to Fig. 21).

\[
K_{e1} = K_0 C_d C_{Dh} C_{Dj} C_{Si} + C_{Dh} + C_{Dj} + C_{Si} + C_{Sj}
\]

\[
\begin{align*}
(20) \\
(i, j) = (1, 2) \text{ or } (2, 1), C_d = 1 \text{ (surcharge flow)}
\end{align*}
\]
\[ K_0 = 0.702 \left( \frac{b}{D_i} \right)^{0.65} \]  

(21)

\[ C_Q = \alpha_1 \left( \frac{Q}{Q_i} - 0.5 \right) + 0.4 \quad \left[ 0.5 \leq \frac{Q}{Q_i} \leq 1 \right] \]  

(22)

\[ C_Q = \alpha_2 \left( 0.5 - \frac{Q}{Q_i} \right) + 0.4 \quad \left[ 0 \leq \frac{Q}{Q_i} \leq 0.5 \right] \]  

(23)

\[ C_{\alpha} = \alpha_3 \left( \frac{D_i}{D_j} \right)^4 - 1 \left[ 1 - \left( \frac{Q}{Q_i} \right)^{1.75} \right] \]  

\[ + \alpha_4 \left( \frac{D_i}{D_j} \right)^4 - 1 \left[ 1 - \left( \frac{Q}{Q_i} \right)^{0.89} \right] \]  

\[ C_{\beta} = \alpha_5 \left( \frac{D_i}{D_j} \right)^4 - 1 \left[ 1 - \left( \frac{Q}{Q_i} \right)^{0.28} \right] \]  

\[ + \alpha_6 \left( \frac{D_i}{D_j} \right)^4 - 1 \left[ 1 - \left( \frac{Q}{Q_i} \right)^{0.95} \right] \]  

\[ C_{\gamma} = 0.35 \left[ S_i + D_j - D_j - D_j - 0.2 \right] \left( \frac{Q}{Q_i} \right)^3 \]  

\[ \left[ 0.2 \leq S_j + D_i - D_j - D_j < 1.2 \right] \]  

\[ C_{\delta} = 0.20 \left[ S_i + D_j - D_j - D_j - 0.2 \right] \left( \frac{Q}{Q_i} \right)^3 \]  

\[ \left[ 0.2 \leq S_j + D_i - D_j - D_j < 1.2 \right] \]  

\[ \alpha_1 = 1.1032 - 1.49(1 - \sin \theta) \left( 1.2 - \frac{S_j + D_j - D_j}{D_j} \right) \]  

(28)

\[ \alpha_2 = -0.2232 - 1.6(1 - \sin \theta) \left( 1.2 - \frac{S_j + D_j - D_j}{D_j} \right) \]  

(29)

\[ \alpha_3 = 0.17(1 - \sin^2 \theta) \left( 1.2 - \frac{S_j + D_j - D_j}{D_j} \right) \]  

(30)

\[ \alpha_4 = 1.408 \left( 1 - \cos^2 \theta \right) \left( 1.2 - \frac{S_j + D_j - D_j}{D_j} \right) \]  

(31)

\[ \alpha_5 = 0.35(1 - \sin \theta) \sin \theta \left( 1.2 - \frac{S_j + D_j - D_j}{D_j} \right) \]  

\[ + 0.35 \frac{S_j + D_j - D_j}{D_j} - 0.2 \]  

(32)

where subscript \( i \) is the number of the inflow pipe targeted for calculation; subscripts \( j \) is the number of the inflow pipe not targeted for calculation; \( C_{\alpha} \) is the coefficient for the diameter ratio \( D_j/D_i \) between inflow pipe \( i \) and the outflow pipe; \( \alpha_{\beta} \) is the coefficient for the diameter ratio \( D_j/D_i \) between inflow pipe \( j \) and the outflow pipe; \( C_{\beta} \) is the coefficient for the drop gap \( S_j \) between inflow pipe \( i \) and the outflow pipe; and \( C_{\gamma} \) is the coefficient for the drop gap \( S_j \) between inflow pipe \( j \) and the outflow pipe.

Equation (21) is formulated based on the calculation formula obtained by the authors’ research on the energy loss at two-way circular drop manhole. In this study, \( C_{\beta} = 1 \) (pressurized flow), \( C_{\alpha} = 1 \) (no plunging flow), and \( C_{\gamma} = 0.95 \) (half benching) as a coefficient for the manhole bottom shape. Equations (22) and (23) are formulated by revising the coefficient based on the equations described in UDDM. Especially, as shown in Fig. 8, Equation (23) is the one newly added, as the energy loss coefficient of inflow pipe 2 becomes a negative value when \( Q_j/Q_i \) is in the range of 0.0–0.2. Equation (24) shows the influence of the diameter ratio \( D_j/D_i \) between inflow pipe \( i \) as the target for calculation and outflow pipe 3. When there is no drop gap between the inflow and outflow pipes and the connecting pipe is the inflow pipe as the target for calculation is 180°, \( \alpha_3 = 0.17 \) and \( \alpha_4 = 0.0 \). For \( \theta_i = 90° \), \( \alpha_2 = 0.0 \) and \( \alpha_5 = 1.408 \), and the influence of \( D_j/D_i \) increases. This is due to the collision of the inflow to the side wall of the manhole at \( \theta_i = 90° \) and the loss of energy that

| \( \theta_i \) | \( \theta_j \) | \( \theta_i = 90° \) | \( \theta_i = 90° \) | \( \theta_i = 90° \) |
|---|---|---|---|---|
| \( \theta_i = 180° \) | \( \theta_i = 90° \) | \( \theta_i = 90° \) | \( \theta_i = 90° \) | \( \theta_i = 90° \) |
| \( K_{\alpha} \) | \( K_{\beta} \) | \( K_{\gamma} \) | \( K_{\delta} \) | \( K_{\epsilon} \) |
| 2 | 1 | 2 | 1 | 2 | 1
| 2 | 1 | 2 | 1 | 2 | 1
| S_i | S_2 | S_1 | S_3 | S_4 | S_5 |
| S_j | S_2 | S_1 | S_3 | S_4 | S_5 |

Table 3 Application range of \( \alpha_{1} - \alpha_{6} \).

\[ \alpha_{\delta} = \left\{ -0.6 + 0.6(1+1.5 \sin \theta_i) \sin \theta_i \right\} \times \left( 1.2 - \frac{S_j + D_j - D_j}{D_j} \right) \]  

(33)

where subscript \( i \) is the number of the inflow pipe targeted for calculation; subscripts \( j \) is the number of the inflow pipe not targeted for calculation; \( C_{\alpha} \) is the coefficient for the diameter ratio \( D_j/D_i \) between inflow pipe \( i \) and the outflow pipe; \( \alpha_{\beta} \) is the coefficient for the diameter ratio \( D_j/D_i \) between inflow pipe \( j \) and the outflow pipe; \( C_{\beta} \) is the coefficient for the drop gap \( S_j \) between inflow pipe \( i \) and the outflow pipe; and \( C_{\gamma} \) is the coefficient for the drop gap \( S_j \) between inflow pipe \( j \) and the outflow pipe.

Equation (21) is formulated based on the calculation formula obtained by the authors’ research on the energy loss at two-way circular drop manhole. In this study, \( C_{\beta} = 1 \) (pressurized flow), \( C_{\alpha} = 1 \) (no plunging flow), and \( C_{\gamma} = 0.95 \) (half benching) as a coefficient for the manhole bottom shape. Equations (22) and (23) are formulated by revising the coefficient based on the equations described in UDDM. Especially, as shown in Fig. 8, Equation (23) is the one newly added, as the energy loss coefficient of inflow pipe 2 becomes a negative value when \( Q_j/Q_i \) is in the range of 0.0–0.2. Equation (24) shows the influence of the diameter ratio \( D_j/D_i \) between inflow pipe \( i \) as the target for calculation and outflow pipe 3. When there is no drop gap between the inflow and outflow pipes and the connecting pipe is the inflow pipe as the target for calculation is 180°, \( \alpha_3 = 0.17 \) and \( \alpha_4 = 0.0 \). For \( \theta_i = 90° \), \( \alpha_2 = 0.0 \) and \( \alpha_5 = 1.408 \), and the influence of \( D_j/D_i \) increases. This is due to the collision of the inflow to the side wall of the manhole at \( \theta_i = 90° \) and the loss of energy that
corresponds to the velocity head, plus the influence of \( D_3/D_i \) becoming larger than in the case of \( \theta=180^\circ \) in which water flows through the manhole easily. The velocity head increases especially when the diameter of the inflow pipe becomes small, and the energy loss at the manhole increases further. When the manhole is connected with a straight-through pipe and influent flows smoothly in the manhole, because the velocity head is a function of the fourth power of the pipe diameter \((v^2/2g=8Q^2/(\pi^2gD^4))\), it is considered in the term, \((D_3/D_i)^4-1\) on the right side of Equation (24) based on Bernoulli’s theory that the water level in the manhole decreases as the diameter of the inflow pipe becomes small. Equation (25) shows the influence of the diameter ratio \( D_3/D_i \) between the outflow pipe and inflow pipe \( j \) that is not targeted for calculation. Especially, when there is no drop gap between the inflow and outflow pipes in the case of \( \theta_j=90^\circ \) and \( \theta_j=180^\circ \), \( a_3=0.0 \) and \( a_6=-0.6 \), and then \( C_i \) \( j < 0 \). This is because the energy loss coefficient \( K_e \) for inflow pipe 2 takes a negative value when \( Q_i/Q_j=0.0-0.2 \) and \( \theta_1 (=\theta_i)=180^\circ \) and \( \theta_2 (=\theta_j)=90^\circ \) as shown in Fig. 10. The reason why the measured value of \( K_e \) indicates a negative value is mentioned above in Chapter 5(2). This effect is not considered by UDDM and is newly added in the proposed formula by the authors. In addition, for Equations (24) and (25), it is possible to change a shape of curve according to the diameter ratio because the influence of diameter ratios \((D_3/D_i\) and \( D_3/D_j \)) is considered not by the product of the coefficient but by the sum of the coefficient.

Equations (26) and (27) are the expressions that can consider the influence of the drop gap between the inflow and outflow pipes based on the calculation formula for the energy loss at two-way circular drop manhole in the previous research by the authors'\(^2\). The influence of the drop gap can be ignored when the drop ratio \((D_3+D_i-D_j)/D_i\) or \((D_3+D_j-D_i)/D_j\) is less than 0.2. Equations (28)–(33) are developed based on the experimental results as shown in Figs. 7–10 and Figs. 15–20. Modification coefficients are made not to depend on the connecting angle of the inflow pipe and to have a constant value when the drop gap between the inflow pipe and outflow pipes increases. The reason is that influence from the inflow pipe collides with the side wall of the manhole with the drop gap (refer to Table 4 for the application range) regardless of the connecting angle of the inflow pipe. In the new proposed calculation formula to estimate the energy loss at the manhole, the variable that expresses the influence of the drop gap of the two opposed inflow pipes is not considered. This is a future task.

(3) Verification and calculation example of proposed formula

The measured values and the calculated values by the proposed formula are compared, validity of the calculation formula is verified, and a calculation example under some conditions is shown as follows. Under the condition of no drop gap between the inflow and outflow pipes, the influence by the changing of the connected inflow pipe angle is indicated in Figs. 22–25. Figures 22 and 23 are for \( D_3/D_i=D_3/D_j=1.0 \). Figures 24 and 25 are for \( D_3/D_i=D_3/D_j=2.0 \). In addition, Fig. 22 and Fig. 24 show the influence of changing of the connecting angle for inflow pipe 1. Figure 23 and Fig. 25 show the influence of changing of the connecting angle for inflow pipe 2.

The value of \( K_{e1} \) \((\theta_1=\theta_2=90^\circ)\) at \( Q_i/Q_j=0.0 \) is made to become equal with the value of \( K_{e2} \) \((\theta_1=180^\circ \text{ and } \theta_2=90^\circ)\) at \( Q_i/Q_j=1.0 \) as shown in Fig. 22. In addition, the value of \( K_{e2} \) \((\theta_1=\theta_2=90^\circ)\) at \( Q_i/Q_j=0.0 \) is made to become equal with the value of \( K_{e1} \) \((\theta_1=180^\circ \text{ and } \theta_2=90^\circ)\) at \( Q_i/Q_j=1.0 \) as shown in Fig. 22. The influence of the drop gap between the inflow and outflow pipes is shown in Figs. 26–29. Figures 26 and 27 are for \( \theta_1=180^\circ \) and \( \theta_2=90^\circ \). Figure 26 shows the influence that changes only the drop for inflow pipe 1. Figure 27 shows the influence as both drops for inflow pipes 1 and 2 change in the same length. As the connecting angle for inflow pipe 1 is fixed at 180°, the influence that changes the connecting angle for inflow pipe 2 is shown in Figs. 28 and 29. Figure 28 is for \( S_1=10\text{cm} \) and \( S_2=3\text{cm} \), and Fig. 29 is for \( S_1=3\text{cm} \) and \( S_2=10\text{cm} \).

The comparison between the measured values and the calculated values by the proposed formula is shown in Figs. 31–36, Figs. 38–43 and Figs. 45–47 (refer to Fig. 30, Fig. 37, and Fig. 44). Figures 31 and 32 show the influence of the diameters of the inflow and outflow pipes when the connecting angles of the two inflow pipes are \( \theta_1=180^\circ \) and \( \theta_2=90^\circ \), and Figs. 33–36 show the influence of the connecting pipe angle, respectively. Moreover, the comparison between the measured values and the calculated values for the pressure loss coefficients is indicated in Figs. 38–43 as reference. Figures 45–47 show the influence of the drop gap between the inflow and outflow pipes in Types A, C, and D, respectively.

As shown in Figs. 31 and 32, the measured values are expressed well overall by the calculated values though a part of the calculated values is not suitable for the measured values in Types B, C, and D in Fig. 31. As indicated in Figs. 33–36, the measured values are reproduced by the calculated values, even if the connecting angle between the inflow and outflow pipes is changed. In addition, as shown in Figs.
**Fig. 22** Influence of horizontal connecting angle, $\theta_1$ of inflow pipe 1
($D_1=D_2=D_3=5\text{cm}$, without drop gap between inflow and outflow pipes).

**Fig. 23** Influence of horizontal connecting angle, $\theta_2$ of inflow pipe 2
($D_1=D_2=3\text{cm}$ and $D_3=6\text{cm}$, without drop gap between inflow and outflow pipes).

**Fig. 24** Influence of horizontal connecting angle, $\theta_1$ of inflow pipe 1
($D_1=D_2=3\text{cm}$ and $D_3=6\text{cm}$, without drop gap between inflow and outflow pipes).

**Fig. 25** Influence of horizontal connecting angle, $\theta_2$ of inflow pipe 2
($D_1=D_2=3\text{cm}$ and $D_3=6\text{cm}$, without drop gap between inflow and outflow pipes).
a) Relationship between $K_{e1}$ and $Q_2/Q_3$

b) Relationship between $K_{e2}$ and $Q_2/Q_3$

Fig. 26 Influence of drop gap $S_1$ of inflow pipe 1 ($D_1=D_2=3\text{ cm}$ and $D_3=6\text{ cm}$, $\theta_1=180^{\circ}$ and $\theta_2=90^{\circ}$, $S_2=3\text{ cm}$).

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Fig. 27 Influence in the condition as $S_1=S_2$ ($D_1=D_2=3\text{ cm}$ and $D_3=6\text{ cm}$, $\theta_1=180^{\circ}$ and $\theta_2=90^{\circ}$).

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Fig. 28 Influence of horizontal connecting angle, $\theta_2$ of inflow pipe 2 at $S_1=10\text{ cm}$ and $S_2=3\text{ cm}$ ($D_1=D_2=3\text{ cm}$ and $D_3=6\text{ cm}$, $\theta_1=180^{\circ}$).

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Fig. 29 Influence of horizontal connecting angle, $\theta_2$ of inflow pipe 2 at $S_1=3\text{ cm}$ and $S_2=10\text{ cm}$ ($D_1=D_2=3\text{ cm}$ and $D_3=6\text{ cm}$ and $\theta_1=180^{\circ}$).
**Fig. 30** Plane view of manhole (Difference of connecting pipe angle).

**Fig. 31** Comparison between measured values and calculated values by proposed formula for inflow pipe 1.

**Fig. 32** Comparison between measured values and calculated values by proposed formula for inflow pipe 2.

**Fig. 33** Measured and calculated values for inflow pipe 1 (Influence of horizontal connecting pipe angle).

**Fig. 34** Measured and calculated values for inflow pipe 2 (Influence of horizontal connecting pipe angle).

**Fig. 35** Measured and calculated values for inflow pipe 1 (Influence of horizontal connecting pipe angle).

**Fig. 36** Measured and calculated values for inflow pipe 2 (Influence of horizontal connecting pipe angle).
Fig. 37 Plane view of manhole (Difference of connecting pipe angle).

Fig. 38 Pressure loss coefficients by proposed calculation formula and measured values for inflow pipe 1.

Fig. 39 Pressure loss coefficients by proposed calculation formula and measured values for inflow pipe 2.

Fig. 40 Comparison of pressure loss coefficient for inflow pipe 1 (Influence of horizontal connecting pipe angle).

Fig. 41 Comparison of pressure loss coefficient for inflow pipe 2 (Influence of horizontal connecting pipe angle).

Fig. 42 Comparison of pressure loss coefficient for inflow pipe 1 (Influence of horizontal connecting pipe angle).

Fig. 43 Comparison of pressure loss coefficient for inflow pipe 2 (Influence of horizontal connecting pipe angle).
Fig. 44 Manhole and pipes (With drop gap between inflow and outflow pipes).

Fig. 45 Comparison between measured values and calculated values (Influence of drop gaps $S_1$ and $S_2$, Type A).

Fig. 46 Comparison between measured values and calculated values (Influence of drop gaps $S_1$ and $S_2$, Type C).

Fig. 47 Comparison between measured values and calculated values (Influence of drop gaps $S_1$ and $S_2$, Type D).
45–47, even if the drop gap is installed for $\theta_1=180^\circ$ and $\theta_2=90^\circ$, the calculated values by the proposed formula reproduce the measured values well.

7. CONCLUSIONS

The main findings obtained in this study are as follows:

1) When $\theta_1=180^\circ$ and $\theta_2=90^\circ$ at the manhole with no drop gap among the two inflow pipes ($D_1=5\text{cm}$) and $Q_2/Q_1$ ($Q_1$ is the flow rate of pipe $i$) is about 0.5, the energy loss coefficient $K_e$ for inflow pipe 1 becomes the maximum value. For $Q_2/Q_1=1.0$, when diameter $D_2$ of inflow pipe 2 is fixed and diameter $D_1$ of inflow pipe 1 is reduced, $K_e$ becomes minimum and increases as $Q_2/Q_1$ decreases. The energy loss coefficient $K_e$ becomes small as $Q_2/Q_1$ decreases. Especially, when $Q_2/Q_1$ is in the range of 0.0–0.2, $K_e$ becomes a negative value and as the diameter of inflow pipe 1 is reduced, a negative value of $K_e$ becomes larger.

2) $K_e$ for $\theta_1=\theta_2=90^\circ$ increases more than $K_e$ for $\theta_1=180^\circ$ and $\theta_2=90^\circ$ except about 0.5 in $Q_2/Q_1$, when the combination of the diameter of the inflow and outflow pipes is the same, and the diameter of inflow pipe 2 is small. This depends on the influence of bending at the manhole bottom and the influence of two opposed inflow pipes. When $Q_2/Q_1<0.5$, $K_e$ in $\theta_1=\theta_2=90^\circ$ takes a large value and when $Q_2/Q_1>0.5$, there is little difference in $K_e$ even if $\theta_1$ is changed from $180^\circ$ to $90^\circ$. This is because when $Q_2/Q_1>0.5$, the influence of the connecting angle for inflow pipe 1 becomes small and the influence of bending between inflow pipe 2 and outflow pipe is predominant.

3) When $Q_2/Q_1<0.5$, both $K_e$ and $K_e$ increase if the drop gap is installed between the inflow straight-through pipe ($\theta_1=180^\circ$) and the outflow pipe. This is because influent from the inflow pipe collides to the inside wall of the manhole exit with the drop.

4) Even if the drop is installed in the lateral inflow pipe ($\theta=90^\circ$), the influence for $K_e$ and $K_e$ is small. This is because influent from the lateral inflow pipe collides to the side wall of the manhole regardless of the presence of the drop.

5) When the size of the drop gap between the inflow and outflow pipes exceeds the diameter of the outflow pipe, the influence that the difference of the size of the drop gives to the energy loss coefficient is very small.

6) At the manholes with no drop gaps between the inflow and outflow pipes (crown alignment), the proposed formula is applicable to the range of $90^\circ \leq \theta_1, \theta_2 \leq 180^\circ$. At the manholes with drop gaps between those pipes, the proposed formula is applicable to $\theta = 180^\circ$ (fixed) and the range of $90^\circ \leq \theta < 180^\circ$ as another connecting angle between those pipes.

In the future, more improved calculation formula on energy loss at the manhole will be developed based on experimental results obtained by changing the drop gap at manhole with two opposed inflow pipes.

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