Energy losses at three-way circular drop manholes under surcharged conditions
Shinji Arao, Tetsuya Kusuda, Katsumi Moriyama, Shunsuke Hiratsuka, Jyunsaku Asada and Nozomu Hirose

ABSTRACT

Energy loss at manholes is of importance in the design of storm sewer networks and in flood-analysis. Some researchers have already investigated the energy loss at three-way manholes under surcharged conditions. However, formulation to calculate the energy loss at manholes, including all variables of structural elements of the pipes and of the manhole has not yet been accomplished. Therefore, more study to formulate the energy loss at three-way drop manholes is needed. In this study, the ratio of the diameter between inflow pipes and an outflow pipe, the ratio of flow rates between those pipes, water depth in a manhole and the drop gaps between those pipes are considered and the energy loss at three-way circular drop manholes is examined. Finally, a modified formula, more accurate than that in the U.S. Federal Highway Administration’s 2001 Urban Drainage Design Manual is proposed. The proposed formula takes the influence of the ratio of the diameter between inflow pipes and outflow pipe and drop gaps between those pipes into consideration. The calculated energy loss coefficients in both straight-through and lateral pipes successfully reproduce the measured values.

Key words | energy loss, junction, manhole, surcharge flow, T-intersection, urban storm drainage

INTRODUCTION

Recently in Japan local governments have published flood hazard maps. This information is useful for inhabitants forced to evacuate during floods. However, flood hazard maps with water depth obtained by numerical simulation are not always sufficiently accurate. One of the reasons is that the energy loss at sewer manholes is not always estimated appropriately in the calculation of the energy-grade lines in storm sewer pipes (U.S. EPA SWMM, 2004; DHI MOUSE, 2008). There is much variation in horizontal and vertical connection patterns of inflow and outflow pipes at manholes. The authors have already proposed a new formula to calculate energy loss at a two-way circular drop manhole with an inflow pipe and an outflow pipe (Kusuda & Arao 1996; Arao & Kusuda 1999, 2005). The number of inflow pipes and drop gaps between inflow pipes and an outflow pipe are the important elements to be considered in design of a manhole at an intersection such as a T-intersection or crossing, and formulating the energy loss at manholes is difficult. Research has already been carried out on the energy loss at three-way manholes under surcharge flow (Sangster et al. 1961; Hare 1983; Lindvall 1984; Marsalek 1985; Yen 1986; Hare et al. 1990; Johnston & Volker 1990; Stein et al. 1999; U.S. FHWA 2001, 2009; Arao & Kusuda 2005; O’Loughlin & Stack 2005). However, formulation to calculate the energy loss at manholes, including all variables of structural elements of the pipes and of the manhole has not yet been accomplished. Therefore, more study is still required on formulation. In this study, firstly the ratio between the diameter of an inflow pipe and that of an outflow pipe, the ratio of flow rate between those pipes, water depth in a manhole and the drop between those pipes were considered, and energy loss at three-way circular drop manholes was examined. The authors have already solved some problems with the formula to estimate energy loss at a three-way manhole described in the Urban Drainage Design Manual (U.S. FHWA 2001). Secondly a modified formula with higher estimation accuracy is proposed.

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EXPERIMENTAL METHODS

Experimental setup and model manholes

The outline of the experimental apparatus is shown in Figures 1 and 2. The experimental conditions for diameters of inflow and outflow pipes, and drops between upstream pipe or lateral pipe and outflow pipe are indicated in Table 1.

Types A-D are four kinds of conventional manholes used in Japan, reduced in a scale of 1/5. The perpendicular connection between inflow and outflow pipes for Types A, C and D is crown or drop alignment and that for Type B is center alignment (Figure 2). It was proven that scaling had little effect on relative energy loss for a manhole model with the diameter of 0.15 m and with the diameter of 0.6 m (Kerenyi & Jones 2006; Kerenyi et al. 2007) and a similar result was confirmed by Lau (2008). Therefore, the results of this study are applicable to the manholes with ordinary dimensions.

Experimental procedure

The flow rate \( Q \) was regulated by two control valves, and was measured by water volume at the downstream tank. The flow rate \( Q \) ranged from 0 to 1.0 l/s in each inlet pipe. The water depth in manhole, \( h \) is the water depth above the internal wall of the top of the upstream pipe, and was measured at four points along the external wall of the manhole as shown in Figures 1 and 3. As illustrated in Figure 4, the total energy head at the inflow and outflow pipes was calculated at distances of 0.3, 0.5 and 0.7 m from the manhole in terms of \( E = h_e + h_p + V^2/2g \), in which \( h_e \): the elevation, \( h_p \): the pressure head, \( V \): the mean flow velocity \((=Q/A, A: \pi D^2/4)\).

The energy loss at a manhole, \( \Delta E^* \) is defined as the difference between the two energy grade lines. The energy loss coefficient, \( K_{e^*} \) is defined as follows:

\[
K_{e^*} = \frac{\Delta E^*}{(V^2/2g)}
\]  

where \( \Delta E_u \): the energy loss for the main straight-through pipe, \( \Delta E_l \): the energy loss for the lateral pipe, \( K_{eu} \): the energy loss coefficient for the main straight-through pipe, \( K_{el} \): the energy loss coefficient for the lateral pipe, \( V_d \): the cross-sectional mean flow velocity in the downstream pipe, \( g \): the gravitational acceleration.

Table 1 | Experimental conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>( D_u )</th>
<th>( D_l )</th>
<th>( D_d )</th>
<th>( S_u )</th>
<th>( S_l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>5 cm</td>
<td>5 cm</td>
<td>5 cm</td>
<td>0 cm, 5 cm</td>
<td>0 cm, 2.5 cm, 5 cm</td>
</tr>
<tr>
<td>Type B</td>
<td>5 cm</td>
<td>5 cm</td>
<td>6 cm</td>
<td>0 cm</td>
<td>0 cm</td>
</tr>
<tr>
<td>Type C</td>
<td>5 cm</td>
<td>4 cm</td>
<td>6 cm</td>
<td>1 cm, 6 cm, 11 cm</td>
<td>2 cm, 7 cm, 12 cm</td>
</tr>
<tr>
<td>Type D</td>
<td>4 cm</td>
<td>5 cm</td>
<td>6 cm</td>
<td>2 cm, 7 cm, 12 cm</td>
<td>1 cm, 6 cm, 11 cm</td>
</tr>
</tbody>
</table>

where \( D_u \): the main upstream pipe diameter, \( D_l \): the lateral pipe diameter, \( D_d \): the downstream pipe diameter, \( S_u \): the drop between the main upstream pipe and the downstream pipe, \( S_l \): the drop between the lateral pipe and the downstream pipe.
Experimental Results

Some examples of the experimental results for Types A, C and D with crown alignment of perpendicular connection between inflow pipes and outflow pipe, and for Type B (center alignment) are shown in Figures 5 and 6. For Types A-D at $Q_l/Q_d = 0$, when $h/D_u$ is less than 1, the energy loss coefficients, $K_{eu}$ and $K_{el}$ increase due to horizontal vortices which corresponds to the manhole diameter. The result was pointed out by Lindvall (1984). When $h/D_u$ is greater than 2, the energy loss coefficients are almost constant. At $Q_l/Q_d = 1$, the loss of the kinetic energy increases, as the inflow from the lateral pipe impacts directly on the sidewall of the manhole and large scale vortices occur in the manhole.

Formula to Predict Energy Losses

The energy loss coefficient, $K_{e^*}$ under surcharge flow for a three-way circular drop manhole is expressed as a function of non-dimensional independent variables and manhole base shape factor as shown in Equation (2). It is assumed that the pipe slope is mild, and that the pipe and manhole are circular.

$$K_{e^*} = f\left(R_e, \frac{Q_i}{Q_d}, \frac{h}{D_u}, \frac{D_i}{D_d}, \frac{y}{D_d}, \frac{S_i}{D_d}, \frac{\theta}{180}, \text{manhole base shape}\right)$$  \(2\)

where $R_e$: Reynolds number, $Q_i$: the inflow flow rate, $Q_d$: the outflow flow rate, $b$: the manhole diameter, $D_i$: the inflow pipe diameter, $D_d$: the outflow pipe diameter, $y$: the water depth in manhole above the outlet pipe invert, $S_i$: the drop between the inflow and outflow pipes, $\theta$: the horizontal connected angle between the inflow and outflow pipes. In the case of $R_e > 10^4$, the effect of $R_e$ is negligible. (Marsalek 1985).

In experiments, the energy loss coefficient, $K_{e^*}$ is defined as Equation (1). The pressure loss coefficient, $K_{p^*}$

![Figure 3](image3.png)  
Water depth, $h$ in manhole.

![Figure 4](image4.png)  
Definition of energy loss, $\Delta E_\ast$.

![Figure 5](image5.png)  
Experimental results of energy loss coefficient, $K_{eu}$. (a) $Q_u/Q_d = 0$, $Q_l/Q_d = 0$; (b) $Q_u/Q_d = Q_l/Q_d = 0.5$; (c) $Q_u/Q_d = 0$, $Q_l/Q_d = 1$.

![Figure 6](image6.png)  
Experimental results of energy loss coefficient, $K_{el}$. (a) $Q_u/Q_d = 0$, $Q_l/Q_d = 0$; (b) $Q_u/Q_d = Q_l/Q_d = 0.5$; (c) $Q_u/Q_d = 0$, $Q_l/Q_d = 1$. 

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is also evaluated from the energy loss coefficient, \( K_{eu} \) as shown in Equation (3):

\[
K_{pu} = K_{eu} + 1 - \left( \frac{V_s}{V_d} \right)^2
\]

(3)

where \( V_s \): the cross-sectional mean flow velocity in an inflow pipe.

\( V_d \) is the cross-sectional mean flow velocity in an outflow pipe. In this study, velocity distributions in the outflow pipe were not measured under surcharged conditions. The velocity distributions do not have much influence in the estimation of energy loss at the manhole under surcharge flow. In Equations (1) and (3), the influence is included in the estimation of the energy loss coefficients, \( K_{eu} \), \( K_{ch} \), \( K_{pu} \) and \( K_{pl} \).

Sangster et al. (1963) examined the effects of the diameter ratios between inflow and outflow pipes, and the diameter ratio between manhole and outflow pipe under surcharged conditions. They developed an equation for pressure head loss coefficients at the manhole (no benching) with a main and perpendicular lateral pipes, as a function of \( b/D_d, Q_i/Q_d, D_i/D_d \) and \( D_d/D_i \) using experimental data and theoretical considerations. However, due to the restriction of the number of experimental data, the applicable range of \( b/D_d \) in the equation is from 1.0 to 2.0. Lindvall (1984) developed an equation for pressure head loss coefficients as a function of \( b/D_d, Q_i/Q_d, D_i/D_d \) at the three-way manhole with half benching and with full benching using the theory of the total energy flux. Marsalek (1985) also studied energy losses at manholes with several base shapes with a main and perpendicular lateral pipes and with two opposite lateral pipes. The experimental results obtained by Marsalek indicated that the theory developed by Lindvall could be applicable. Hare et al. (1990) proposed pressure head loss coefficients as a function of \( D_u/Q_u \) and \( Q_i/D_i \) (inflow pipe number), \( \theta \) (the angle between inflow and outflow pipes) in terms of the momentum equation. In the U.S. FHWA Urban Drainage Design Manual (2001), \( b/D_d, Q_i/Q_d, D_i/D_d, y/D_d, \theta/180 \) (Figure 7) in Equation (2) are taken into consideration and are described below.

The formula for the energy loss coefficient, \( K_E \) at the three-way manhole in the Urban Drainage Design Manual is shown below.

In Equation (4), the effect of the drop between inflow and outflow pipes is not considered.

\[
K_E = K_o C_D C_d C_Q C_p C_B
\]

(4)

\[
K_o = 0.1 \left( \frac{b}{D_d} \right) (1 - \sin \theta) + 1.4 \left( \frac{b}{D_d} \right)^{0.15} \sin \theta
\]

(5)

\[
C_D = \left( \frac{D_d}{D_i} \right)^3
\]

(6)

\[
C_Q = (1 - 2 \sin \theta) \left( 1 - \frac{Q_i}{Q_d} \right)^{0.75} + 1
\]

(7)

where \( C_d = 1 \) (surcharge flow, \( y/D_d \geq 3.2 \), \( C_p = 1 \) (no effect of plunging flow), \( C_B = 0.95 \) (half benching).

**Figure 6** Experimental results for energy loss coefficient, \( K_{eu} \), (a) \( Q_i/Q_u = 1, Q_i/Q_u = 0 \); (b) \( Q_i/Q_u = 0.5 \); (c) \( Q_i/Q_u = 0, Q_i/Q_u = 1 \).

**Figure 7** Angle of horizontally connected pipe.
Figure 8 gives a comparison between measured values and calculated values in terms of Equations (4)–(7) on a three-way circular manhole. Both sets of values are considerably different and vary depending on the ratio of the flow rate in the inflow and outflow pipes and the diameter ratio between those pipes.

To calculate the energy loss coefficient, $K_{eu}$ more precisely, Equations (8)–(16) were proposed by using measured values. In Equations (8) and (9), $C_{ud}$ and $C_{ld}$ are a function of the ratio of pipe diameter, $D_d/D_u$ and $D_d/D_l$ between inflow pipe and outflow pipe, respectively, instead of $C_D$ in Equation (4). $C_{su}$ and $C_{sl}$ indicate the term of drop gaps between inflow and outflow pipes. In Equation (8) for the straight-through pipe, the effect of drop gaps between lateral and outflow pipes is very small, therefore $C_{sl}$ is not considered. Equation (10) is a formula revised by the authors using experimental results for two-way circular drop manhole (Kusuda & Arao, 1996; Arao & Kusuda, 1999, 2005). Equation (11) from the Urban Drainage Design Manual is applicable in the range of $0.5 \leq Q_i/Q_d \leq 1$. For the range of $0 \leq Q_i/Q_d < 0.5$, a new formula (12) based on experimental results is proposed. Pressure head in the manhole decreases as inflow pipe diameter decreases and the flow velocity in the pipe increases. The effect is taken into consideration as the term of $(D_d/D_u)^4 - 1$ or $(D_d/D_l)^4 - 1$ in Equations (13)–(16). The pipe diameter ratio, $D_d/D_u$ between the main upstream pipe and downstream pipe is considered in Equations (13) and (14). Equation (13) is for a straight-through pipe flow, and Equation (14) is for a lateral pipe flow. As the main upstream pipe diameter decreases, the flow velocity in the pipe increases. Therefore, the kinetic energy loss due to the collision of the upper part of expanded inflow against the inside wall of a manhole with crown alignment of connected pipes increases (Figures 2(a) and 9(a)). Also, as the main upstream pipe diameter decreases, the water level in
a manhole falls and the pressure head decreases in the manhole. Therefore the pressure head in a lateral pipe decreases (Figure 9(b)). The pipe diameter ratio, \(D_d/D_l\) between a lateral pipe and a downstream pipe is considered in Equations (15) and (16). Equation (15) is for a straight-through pipe flow, and Equation (16) is for lateral pipe flow. As the lateral pipe diameter becomes small, the flow velocity in the pipe increases. Therefore, the kinetic energy loss due to the collision of inflow against the inside wall of a manhole increases (Figures 9(a) and (b)).

\[
K_{eu} = K_0 C_d C_Q C_p C_B + C_{ud} + C_{id} + C_{Su} \\
K_{el} = K_0 C_d C_Q C_p C_B + C_{ud} + C_{id} + C_{Su} + C_{Sl}
\]

Figure 10 | Comparison between experimental results and calculated values by modified Equations (8)-(20). (a) \(K_{eu}\) and \(Q_l/Q_d\) (b) \(K_{el}\) and \(Q_l/Q_d\) (c) \(K_{eu}\) and \(Q_l/Q_d\) (d) \(K_{el}\) and \(Q_l/Q_d\) (e) \(K_{eu}\) and \(Q_l/Q_d\) (f) \(K_{el}\) and \(Q_l/Q_d\).
\[ K_a = 0.09 \left( \frac{b}{D_a} \right) (1 - \sin \theta) + 1.3 \left( \frac{b}{D_a} \right)^{0.15} \sin \theta \]  

(10)

\[ C_Q = (1 - 2 \sin \theta) \left( 1 - \frac{Q_l}{Q_d} \right)^{0.75} \left( 1 + \frac{Q_l}{Q_d} \right)^{1.5} \]  

by UDDM, 0.5 \leq \frac{Q_l}{Q_d} \leq 1

(11)

\[ C_Q = -0.3872 \sin \theta \left( 2.2525 - \frac{Q_l}{Q_d} \right)^{2} + 1.5946 \]  

\( 0 \leq \frac{Q_l}{Q_d} < 0.5 \)

(12)

\[ C_{ud} = 0.34 \left( \frac{D_d}{D_u} \right)^{4} - 1 \left( 1 - \frac{Q_l}{Q_d} \right)^{1} \]  

(for straight-through pipe, \( \theta = 180^\circ \))

(13)

\[ C_{ud} = -0.75 \left( \frac{D_d}{D_u} \right)^{4} - 1 \left( 1 - \frac{Q_l}{Q_d} \right)^{3} \]  

(for lateral pipe, 90 \( \leq \theta < 180^\circ \))

(14)

\[ C_{ld} = 0.34 \left( \frac{D_d}{D_l} \right)^{4} - 1 \left( \frac{Q_l}{Q_d} \right)^{0.75} \]  

(for straight-through pipe, \( \theta = 180^\circ \))

(15)

\[ C_{ld} = \left( \frac{D_d}{D_l} \right)^{4} - 1 \left( \frac{Q_l}{Q_d} \right)^{2} \]  

(for lateral pipe, 90 \( \leq \theta < 180^\circ \))

(16)

where \( C_d = 1 \) (surcharge flow, \( y/D_d \geq 3.2 \)), \( C_P = 1 \) (no effect of plunging flow), \( C_B = 0.95 \) (half benching), \( C_{ud} \): the coefficient for the diameter ratio between the main upstream pipe and the downstream pipe, \( C_{ld} \): the coefficient for the diameter ratio between the lateral pipe and the downstream pipe.

Comparison between measured values and calculated values by Equations (8)–(16) is shown in Figure 9. Calculated values, \( K_{eu} \) and \( K_{ed} \) mostly reproduce measured values.

The increase of energy loss due to the drop gaps between the main upstream pipe and the downstream pipe is proposed in Equations (17) and (18). Equations (17) and (18) are applied for the estimation of energy loss coefficients, \( K_{eu} \) and \( K_{ed} \). As shown in Figure 10, the calculated values were generally close to the measured values. The increase of energy loss due to the drop gaps between the lateral pipe and the downstream pipe is much smaller (Figures 10 (e) and (f)).

\[ C_{Su} = 1.3 \left( \frac{S_u + D_u - D_d}{D_u} \right)^{3} \left( \frac{Q_l}{Q_d} \right)^{3} \]  

\( 0.2 \leq \frac{S_u + D_u - D_d}{D_u} \) and \( \frac{S_u}{D_u} \leq 1.2 \)

(17)

\[ C_{Su} = 1.3 \left( \frac{0.2D_d + D_a - D_d}{D_u} \right)^{3} \left( \frac{Q_l}{Q_d} \right)^{3} \]  

\( 0.2 \leq \frac{S_u + D_u - D_d}{D_u} \) and \( \frac{S_u}{D_u} > 1.2 \)

(18)

\[ C_{Sl} = 0.35 \left( \frac{S_l + D_l - D_d}{D_l} \right)^{3} \left( \frac{Q_l}{Q_d} \right)^{3} \]  

\( 0 \leq \frac{S_l + D_l - D_d}{D_l} \) and \( \frac{S_l}{D_l} \leq 1 \)

(19)

\[ C_{Sl} = 0.35 \left( \frac{D_d}{D_l} \right)^{3} \left( \frac{Q_l}{Q_d} \right)^{3} \left( \frac{S_l}{D_d} \right) \]  

\( \frac{S_l}{D_d} > 1 \)

(20)

**CONCLUSIONS**

- The energy loss at a three-way manhole changes considerably due to the ratio of the diameter between inflow pipes and an outflow pipe, the ratio of flow rate between those pipes, the water depth in a manhole, and drop gaps between the pipes.
- Experimental results indicate that the energy loss due to the drop between the lateral and downstream pipes is quite small.
- In the proposed new formula, the effects of the ratio of the diameter between inflow pipes and an outflow pipe and the drop gaps between inflow pipes and outflow pipe are taken into consideration.
- Calculated energy loss coefficients by the proposed formula in both straight-through and lateral pipes reproduce the measured values.

When residents evacuate along a street in floods, the flooded area and water depth in the early stage of flooding are very important. The proposed formula brings more precision to flood hazard mapping used for disaster prevention.
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