Effect of manhole molds and inlet alignment on the hydraulics of circular manhole at changing surcharge

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Abstract

Head loss coefficient of a manhole is dependent on various hydraulic and structural characteristics. This study analyses the effect on manhole head loss coefficients using numerical VOF model due to three factors: manhole structural mold shapes, small changes in inlet orientations and changes in the manhole to inlet pipe ratios. Head loss coefficients showed a strong dependence on the available surcharge. Presence of sump created the maximum head loss while benching provided the best efficiency. Within small deviation of inlet pipe orientations, two different hydraulic regimes were observed indicating effects on both head loss coefficients and threshold surcharge heights. Change of manhole to inlet pipe diameter ratios ($\Phi_m/\Phi_p$) showed three head loss characteristics. Head loss in small manholes ($\Phi_m/\Phi_p<3$) did not change with surcharge. Medium manholes ($3<\Phi_m/\Phi_p<4.0$) showed high head losses up to a specific surcharge. Big manholes ($\Phi_m/\Phi_p>4.5$) showed a high head loss at all the surcharges.

1. Introduction

Manhole is a prevalent structure placed typically at a drainage network connection where a change in pipe direction or gradient is essential (Butler and Davies, 2011). The flow inside a manhole usually is three-dimensional, turbulent and possibly multiphase. After entering the manhole, the flow encounters a sudden expansion and contraction which involves local energy losses. This energy loss makes it an essential element for storm network modeling consideration. The urban drainage system is usually designed to operate without surcharging. In normal condition, the water level at any point remains below the crown level of its conduit creating a gravity-driven flow. However, during extreme rainfall, the conduit water level increases and makes the system pressurized following surcharging manholes. The surcharge creates an additional head loss to the drainage network which becomes significant for an extensive network with several manholes.

Most urban flood models consider manhole head loss while evaluating flood risks (Martins et al., 2017). However, the urban flood models are one or two-dimensional utilizing St. Venant Equations and therefore cannot represent the three-dimensional complex flow pattern of manholes (Leandro et al., 2009; Rubinato, Martins, and Shucksmith, 2018). Instead, they consider the manhole as a point entity and the complex flow is modeled using empirical equations for different local losses (Djordjevic et al., 2005; Leandro and Martins, 2016; Mark et al., 2004). Proper calibration of these empirical equations and thus applying manhole head losses correctly is challenging and considered a source of uncertainty in many urban flood models (Rubinato, Martins, and Shucksmith, 2018). The head loss has a complex nature and can be governed by an almost infinite variety of geometrical and hydraulic factors (O’Loughlin and Stack, 2002). Some of the important factors are the inflow rate, shape of a manhole, surcharge condition, connecting pipe size, angle of connection, pipe to manhole diameter ratios among others (Arao et al., 2012; Carvalho and Leandro, 2012; Jo, Kim, and Yoon, 2018; Marsalek, 1984; Sangster et al., 1958).

Due to several design criteria and practices, different manhole molds with various bottom characteristics can be seen in many countries. They can be distinguished according to the presence or of benching or sump zone, which can influence the head loss of a drainage network differently (Ásztey, 1995; Bo Pedersen and Mark, 1990). Studies suggest that the manhole bottom mold can govern the shape and expansion of the inlet jet and may create head losses differently (Mark and Ilesanmi-Jimoh, 2017; Stovin, Bennett, and Guymers, 2013). Howarth (1985), Bo Pedersen and Mark (1990) and Arao and Kusuda (1999) investigated different scaled manhole molds at the surcharged condition. However, the literature lacks a proper comparison of different manhole mold effects on head loss at surcharge and inflow variations.

A change in the different manhole inlet orientations may also create changes in head loss coefficients. Previous investigations on this issue included the study of sharp bending angles between the inlet and the outlet pipe which are typically seen in a pipe network design, such as bending angles 135° (Arao and Kusuda, 1999; Pfister and Gisonni, 2014), 90° (Arao and Kusuda, 1999; Pfister and Gisonni, 2014; Zhao, Zhu, and Rajaratnam, 2008) and any angles between 90° and 135° (Frost, 2006; Shukry, 1950). However, studies on the effect of small bending angles in the drainage network are rare, such as bend angles between 165° and 180°. Such bending angles are rarely designed in a network, however, may fall within the limit of construction and design deviations. These bending conditions...
are so close to straight inline manholes that their additional effects on the drainage network are sometimes overlooked and considered within the range of uncertainty.

The head loss of a manhole is also dependent on the ratio between the diameters of a manhole and its inlet-outlet pipe(s). Studies indicated that with the decrease in the manhole to pipe diameter ratios the head loss coefficients decrease, therefore increasing the hydraulic performance (Arao et al. 2012; Bo Pedersen and Mark 1990; Guymer and O’Brien 2000; Howarth 1985). Bo Pedersen and Mark (1990) explained the head loss coefficient to be proportional to manhole to pipe diameter ratio, where the proportional constant is dependent on the manhole mold type. However, this characteristic was not checked for other types of manholes, such as manholes containing sump zone.

The current study investigates the effect of flow hydraulics and head losses due to three different factors: (a) due to the difference in manhole mold types, (b) due to changes in the small bending between the inlet and outlet pipes and (c) due to change in the manhole to pipe diameter ratios. The hydraulic models were prototype scale manholes and comparable to the physical size generally found in urban drainage networks. Analysis has been done using validated CFD models utilizing open source toolbox OpenFOAM®.

2. Methodology

2.1. Manholes considered for analysis

Three different inline manholes were chosen to analyze the hydraulic effects of different manhole molds. Each manhole had a diameter of 1.0 m ($\Phi_m$), connected with a 300 mm ($\Phi_p$) inlet-outlet pipe. The geometrical and structural differences in these three manholes were taken from three existing laboratory manhole models. Type A replicates an existing manhole at the University of Coimbra Hydraulic laboratory at its prototype dimensions. This manhole has a bottom sump zone with a depth of 100 mm from the inlet pipe invert level. Type B exists at the University of Sheffield Hydraulic laboratory as a scaled form. This manhole does not have a sump, and its bottom level is merged with the inlet pipe invert. Type C manhole also exists as prototype size at University of Coimbra Hydraulic laboratory and has a U-type invert to give it a more hydraulically shaped bottom. The inlet-outlet pipes at all the three manhole models had a 1:1000 slope towards the downstream. The ratio between the manhole and inlet pipe diameters ($\Phi_m/\Phi_p$) in all the three cases was 3.33. The three investigated manholes are shown in Figure 1(a).

The effect of small inlet orientation angle was investigated on Type A manhole. The outlet pipe orientation was slightly rotated making four different cases, with bending angles of 178°, 175°, 170° and 165°, respectively (Figure 1(d)).

For the investigations of the manhole to pipe diameter ratios, Type A was further explored. For this case, eight additional manhole models were considered having $\Phi_m/\Phi_p$ from 1.5 to 5.0 at different intervals. The inlet-outlet pipe diameter was kept 300 mm like previous cases, and the manhole diameters were changed accordingly to match required manhole to pipe ratios.

2.2. Numerical model procedures and boundary conditions

The manhole hydraulic models considered in this study were fully surcharged manholes, connecting full pipe flows. However, the water level at the manhole chamber was unknown and needed to be considered to calculate the head loss. For this reason, a numerical model with the free surface flow was used in this work. Open source CFD tools
OpenFOAM® v5.0 was utilized in this work applying the solver \textit{interFoam}, which considers the fluid system as isothermal, incompressible and immiscible two-phase flow. The solver utilizes Volume of Fluid (VOF) method (Hirt and Nichols 1981) to capture the free surface location using a single set of Navier-Stokes equations for both fluids. VOF model uses additional equations to describe the free-surface (Carvalho, Lemos, and Ramos 2008) and both fluids share the same velocity at the interface. The solver uses Reynolds averaged conservation of mass and momentum equations for incompressible flow (Jasak 1996; Rusche 2002). The surface tension force acting at the two fluids’ interface is calculated after Brackbill, Kothe, and Zemach (1992). Beg et al. (2018) describes the details of the mathematical equations involved in this model.

The modeling procedure followed two previous complementary works: Beg et al. (2018) and Beg, Carvalho, and Leandro (2018). In the first study, stereo PIV analysis was done in a scaled Type B manhole model, and the measured velocity was compared with the CFD model. The study made four different RANS model, namely, RNG k-\(\varepsilon\), Realizable k-\(\varepsilon\), SST k-\(\Omega\), and LRR. Comparison to PIV data showed that SST k-\(\Omega\) model and RNG k-\(\varepsilon\) model has better accuracy in replicating the complex flow in the scaled manhole. The SST k-\(\Omega\) model requires the application of very small mesh with \(y^+\) below 5 to resolve the boundary flow which makes it significantly computationally expensive. Alternatively, the RNG k-\(\varepsilon\) model showed almost similar accuracy utilizing mesh consisting of 30 < \(y^+\) <300. On the other hand, both Realizable k-\(\varepsilon\) and LRR models overestimated the water level and pressure at the manhole. For this reason, the RNG k-\(\varepsilon\) model was chosen for this study. Beg, Carvalho, and Leandro (2018) study replicated a real scale Type A manhole and validated a CFD model comparing discharge and water depth data measured at the laboratory. The CFD model replicated the flow structure in the manhole effectively which was also comparable to the literature. The inlet flow rates examined in that study were \(30 \times 10^{-3}\) m\(^3\)/s, \(60 \times 10^{-3}\) m\(^3\)/s, \(90 \times 10^{-3}\) m\(^3\)/s, and \(120 \times 10^{-3}\) m\(^3\)/s. The current study also follows the same flow rates and the same model parameters.

Table 1. Combinations of numerical simulations to check effects of manhole mold, inlet orientations and manhole to pipe ratios.

| Purpose                          | Manhole Types | Inlet orientations | Manhole to pipe ratio | Inlet Discharges \((\times10^{-3}\) m\(^3\)/s) | Outlet pressure heads (m) | No of Simulations |
|----------------------------------|---------------|--------------------|-----------------------|-----------------------------------------------|---------------------------|-------------------|
| Effect of manhole mold           | Type A        |                    |                       | 0.4, 0.425, 0.45, 0.5, 0.55, 0.6, 0.7 and 0.8 | 32                        |                   |
|                                  | Type B        | 180°               | 3.3                   | 30, 60, 90, 120                               |                           | 32                |
|                                  | Type C        |                    |                       |                                               |                           | 32                |
| Sub Total: 3 types               |               | 1 type             | 4 options             | 8 options                                     |                           | 96                |
| Effect of inlet orientations     | Type A        | 178°               | 3.3                   | 30, 60, 90, 120                               |                           | 32                |
|                                  | Type A        | 175°               | 3.3                   | 0.4, 0.425, 0.45, 0.5, 0.55, 0.6, 0.7 and 0.8 |                           | 32                |
|                                  | Type A        | 170°               | 3.3                   |                                               |                           | 32                |
|                                  | Type A        | 165°               | 3.3                   |                                               |                           | 32                |
| Sub Total: 1 type                |               | 4 types            | 4 options             | 8 options                                     |                           | 128               |
| Effect of Manhole to pipe ratios | Type A        | 180°               | 3.1                   | 1.5                                           |                           | 8                 |
|                                  | Type A        | 180°               | 3.2                   | 2.0                                           |                           | 8                 |
|                                  | Type A        | 180°               | 3.3                   | 2.5                                           |                           | 8                 |
|                                  | Type A        | 180°               | 3.4                   | 3.0                                           |                           | 8                 |
| Sub Total: 1 type                |               | 9 types            | 1 option              |                                               |                           | 90                |

Three open boundaries; i.e. atmosphere, inlet and outlet (Figure 1(c)) are used in the model. The inlet boundary conditions were prescribed as a fully developed steady flow considering inverse power pipe flow profile (Beg et al. 2018; Çengel and Cimbala 2006). Fixed pressure boundaries were prescribed at the outlet boundary conditions. The pressure at atmosphere boundary was set as equal to atmospheric pressure and \texttt{zeroGradient} for velocity to have free airflow if required. All the close wall boundaries were prescribed as \texttt{noSlip} condition.
were kept 4.5 m each, which was 15Φ_p. A mesh analysis was done following the Richardson extrapolation method reported by Celik et al. (2008). Following the analysis, the interior mesh size was chosen as 20 mm for all the manhole models. The boundary mesh sizes at all close boundaries were further reduced to 2 mm, keeping three boundary layers of increasing cell size. The mesh analysis is presented at Beg, Carvalho, and Leandro (2017) as well as in Appendix 1. Figure 1(b) shows the computational meshes of Type A, B, and C manholes.

2.4. Identification of manhole head loss coefficient and threshold surcharge

When the pipe flow passes through a manhole, it experiences a sudden expansion and compression at the manhole entrance and exit, respectively, which are the main sources of the energy loss. The head loss coefficient, K is calculated using the following equation:

\[ K = \frac{\Delta H}{v^2/2g} \]  

where \( \Delta H \) is the change of energy head at the manhole center, and \( v \) is the averaged flow speed towards the flow direction at the outlet pipe. Figure 2(a) explains the change in energy head in a manhole. Energy grade lines are calculated at the inlet and outlet pipes and then extrapolated to the manhole center. The difference between the two lines gives the change of energy head, \( \Delta H \). The surcharge height (s) is the difference between the water level and the outlet pipe soffit level. Surcharge ratio (s/Φ_p) was calculated from each simulation results, as the ratio between surcharge heights and inlet pipe diameters. At fewer cases, the surcharge ratio was also calculated as the ratio of manhole diameter (s/Φ_m). Later, plots of head loss coefficients vs surcharge ratios were drawn.

3. General hydraulics of a surcharged manhole

When the flow enters a manhole, the flow expands near the manhole inlet and contracts near the outlet (Figure 2(a)). The head loss coefficients of a surcharged manhole vary according to the available surcharge. Previous studies showed that at very small surcharge condition, the head loss increases rapidly without following any trend (Arao and Kusuda 1999; Beg, Carvalho, and Leandro 2018; Bo Pedersen and Mark 1990). This

| Parameter Name                  | Parameter value                                      |
|----------------------------------|------------------------------------------------------|
| Mesh type                        | Hexahedral, Unstructured                             |
| Inlet boundary                   | Velocity inlet, Fully developed velocity profile     |
| Outlet boundary                  | Pressure boundary, hydrostatic pressure              |
| Atmospheric boundary             | Atmospheric pressure                                 |
| Wall boundary                    | noSlip, no roughness                                 |
| Mesh size                        | 20 mm                                                |
| Boundary mesh size               | 2 mm and 3 layers with increasing size               |
| y+ size                          | 30 < y+ < 300                                        |
| Solver                           | VOF                                                  |
| Turbulence                       | RNG k-\epsilon                                      |
| Pressure-Velocity coupling       | PIMPLE                                               |
| Pressure                         | Preconditioned conjugate gradient (PCG)              |
| Velocity                         | symmetric Gauss Seidel                               |
| Near wall treatment              | wallFunction                                         |

In the current study, manhole surcharge was created using the combination of both high upstream flow as well as downstream water pressure. Table 1 presents combinations used in different simulations considering inlet and outlet boundaries. For checking the head loss coefficients at different manhole molds and pipe orientations, eight different outlet pressures were applied for each of the four different discharge condition (30, 60, 90 and 120 \( \times 10^{-3} \) m\(^3\)/s). To calculate the inlet turbulent boundary values of \( k \), \( \nu \), and \( nut \), 5% turbulence intensity was considered. The walls use turbulent wall\( \text{f}unction \) boundary conditions which eliminates the requirement of fine layered boundary mesh construction and hence improves the computational time demand (Greenshields 2015). The model parameters follow a previously validated surcharge manhole model (Beg, Carvalho, and Leandro 2018). Table 2 shows a list of all the parameters used in the model. Figure 1(c) shows the numerical simulation scheme with the open boundary locations.

The maximum Courant–Friedrichs–Lewy (CFL) number was kept as 0.8. Cluster computing system at the University of Coimbra was used to run the simulations using MPI mode. Each simulation was run for 120 s. The first 100 s were required to reach steady state condition and the results of the last 20 s were saved at an interval of 0.1 s as 201-time steps. All the analysis in this study uses averaged data of the last 201-time step results.

2.3. Computational domain and mesh

The computational meshes for the current study were generated using cfmesh v1.1 (Juretić 2015). The inlet and outlet pipe lengths

![Figure 2. (a) Head loss in a surcharged manhole, adapted from Beg, Carvalho, and Leandro (2017); and (b) General hydraulics of a surcharged manhole.](image-url)
phenomenon can be explained by submerged jet theory, originally described by Albertson et al. (1950) at Figure 2(b). According to the theory, when the inlet flow enters a manhole, the incoming flow acts like a submerged jet and divides into two different zones. The fast jet flow zone, known as the core region, starts to shrink its size as the jet travels towards the outlet and takes a conical shape. Consequently, a second zone, known as the diffusion zone, expands as the jet travels. Theoretically, the diffusion region expands at a rate of 1:5 while the core region contracts at 1:6.2 as the jet travels inside the manhole. At the mentioned rate, the diffusion zone may expand up to 0.2Φm towards the vertical direction before reaching the outlet of the manhole. This height is known as threshold surcharge (Lau, Stovin, and Guymer 2008; Stovin, Bennett, and Guymer 2013). If the available surcharge in the manhole is below the threshold, the diffusion zone velocity interacts with the free surface of the manhole and creates an additional head loss. Surcharge below or above the threshold value is known as ‘pre-threshold surcharge’ and ‘post-threshold surcharge’, respectively (Bennett 2012; Lau 2008; Stovin, Bennett, and Guymer 2013). At post-threshold surcharge, a manhole head loss coefficient is expected to be independent of its surcharge.

4. Results and discussions

4.1. Comparison of head loss values with the literature

The results obtained through Type B and C manholes were compared with the manhole head losses already calculated in different literature. Arao and Kusuda (1999) tested the head loss in Type B manhole where Φm/Φp was 3.6. Stovin, Bennett, and Guymer (2013) compared Type B manholes of different sizes using CFD models. One manhole had Φm/Φp = 3.5, which was the closest to the current study and hence used in the comparison (Figure 3 left panel). Arao and Kusuda (1999) found the manhole head loss to be up to 1.25, while Stovin, Bennett, and Guymer (2013) found the maximum head loss as approximately 0.8. The current study tested four different discharge conditions, and the highest head loss varied between 0.6 and 0.8. Current study showed threshold surcharge around 0.75Φm (−0.225 Φm) in Type B manhole, whereas the findings of Arao and Kusuda (1999) showed the threshold surcharge in the range of 1.40Φm (−0.39 Φm). However, Stovin, Bennett, and Guymer (2013) found the threshold surcharge around 0.20Φm, which was similar to our findings.

Lindvall (1986) measured head loss in Type C scaled manhole with Φm/Φp = 4.1. Current study results (Figure 3, right panel) showed good agreement to their data. The maximum head loss coefficients at pre-threshold condition were found the same, up to 0.3. The surcharge threshold observed in Lindvall (1986) was around 1.40Φm. While in the current CFD model, the threshold surcharge was found in the range of 1.10Φm. However, if the surcharge was compared as a ratio of manhole diameter (Φm), both two threshold surcharges are equivalent to 0.33 Φm, as the value of Φm/Φp is different in these cases.

Marsalek (1984) tested head loss in both Type B and Type C inline manholes using laboratory experiments. The work did not describe head loss variation for change of surcharges, instead described a range of head loss for each manhole type using a manhole with Φm/Φp = 1.93, which was much smaller than those of the current tests. The found head loss coefficients were 0.195–0.225 for Type B and 0.105–0.137 for Type C manhole. These values were smaller compared to the current results. This deviation is an expected phenomenon as the head loss coefficient is expected to decrease with the increase in Φm/Φp (Bo Pedersen and Mark 1990). Sangster et al. (1958) also examined Type B manhole for different manhole sizes and described the head losses as a linear relationship to the manhole to pipe diameter ratios, such as:

\[ K = 0.07 \frac{\Phi_m}{\Phi_p} \]  

which calculates the head loss coefficient of the currently studied manhole as 0.233. This value is also lower than those found in this work at below threshold surcharge region. However, at surcharges more than the 0.80Φp, the differences of the head loss coefficients are very low and can be neglected.

Figure 3. Head loss coefficients comparison for manhole Type B (left panel) and Type C (right panel).
4.2. Head loss coefficients at different manhole molds

The surcharge ratios and the head loss coefficients calculated for the three different manhole molds types are plotted in Figure 4. Type A and Type B showed comparably higher head loss coefficients in all scenarios than those of manhole Type C. All manholes showed higher head loss coefficients at low surcharge conditions.

For both Type A and Type B manholes, the head loss coefficients stayed around 0.35 and 0.3, respectively, at a high surcharge (for $s/\Phi_m>0.20$ or $s/\Phi_p>0.67$) with all inflow conditions. The theoretical threshold surcharge of $0.2\Phi_m$ is shown with a dotted line at each graph, which indicate a 200 mm of surcharge height at the manhole and equivalent to the line $s/\Phi_p = 0.67$ as $\Phi_m/\Phi_p = 3.33$. Figure 4 shows that the threshold surcharge for these two manhole types was close to the theoretical value of $0.2\Phi_m$.

However, the head loss coefficient for manhole Type C was much higher than 0.1 at a very low surcharge and remained high up to a surcharge ratio of $s/\Phi_m = 0.33$ (i.e., $s/\Phi_p = 1.11$). The benching in the manhole confined the round jet and minimized the head loss coefficient. The phenomenon can be checked in Figure 5, which illustrates the velocity profiles at the center line $(y = 0 \text{ m})$ of the three manholes at conditions such as $0.20 < s/\Phi_m < 0.33$. The figure shows Type A and B had steady flow at this surcharge level. On the contrary, jet velocity at Type C manhole expanded more towards the vertical and collided with the free surface resulting oscillation through the manhole surface and outlet pipe. This indicated that the threshold surcharge level for Type C manhole is higher than $0.20\Phi_m$. Considering Figure 4, it is apparent that the threshold surcharge for Type C manhole is around 33% of the manhole diameter.

At surcharge below threshold region, the head loss coefficient ($K$) vs Surcharge ratio ($s/\Phi_p$) plot do not follow any trend, which also supports results described in the literature. The head loss coefficients decreased again for all three manholes at very low surcharge conditions (for $s/\Phi_m<0.06$).

It should be noted that a difference in the Type A results can occur if the manhole sump zone depth, i.e., the distance between the pipe invert and the manhole bottom is different.

![Figure 4](image.png)

**Figure 4.** Manhole head loss coefficient ($K$) vs surcharge ratio ($s/\Phi_o$) for manhole types A, B, and C.

![Figure 5](image.png)

**Figure 5.** Instantaneous axial velocity profiles of the three manhole types at the central axis.
Considering the comparison between Type B and Type A, it is expected that the head loss coefficients should increase when the sump depth increases. However, theoretically, a horizontal jet flow may disperse vertically up to 20% of the manhole diameter (Albertson et al. 1950). So, the highest head loss coefficient is assumed at Type A manhole where the sump depth is 20% of the manhole diameter.

### 4.3. Change in head loss coefficients due to pipe bending

To analyze the changes in the flow hydraulics due to small bending, velocity structures at the horizontal section passing through the pipe axis are shown for different pipe bending in Figure 6. All the results are showing time-averaged velocity condition inside the manhole for inlet flow of \(60 \times 10^{-3} \text{ m}^3/\text{s}\) with the downstream condition of 0.6 m of water head.

At straight pipe flow (regular condition/180° pipe) of the manhole (Figure 6(a)), the core zone with strong velocity could enter the outlet pipe without much variation. This condition changed with the alteration in inlet-outlet orientation. At smaller bending angles, such as 178° and 175° angles (Figure 6(b,c)), the core velocity region could still enter the outlet pipe without much variation. However, at sharper bending angles such as 170° or 165° angles (Figure 6(c,d)), the core jet was discontinued. Although the central axis of the inlet pipe could still point towards the outlet pipe, the outlet pipe could not accommodate the full width of the core jet region. Part of the core zone hit the manhole wall resulting discontinuity in the jet. At these bending situations, the whole jet became weak or discontinued, making comparably higher contribution the manhole head loss. These phenomena are reflected in Figure 7, which shows the variation in head loss coefficients due to different inlet orientations.

Figure 7 indicates that the bent pipe shows an overall similar qualitative head loss coefficient trends when compared to the similar plot at the normal condition of Manhole Type A (Figure 4 left panel), i.e. high head loss at a pre-threshold surcharge and comparatively lower head loss at post-threshold surcharge. At 178° bend, the post-threshold surcharge head loss coefficient was close to 0.38, which was very close to the similar condition value of straight pipe (below 10% increase). At 175° orientation, the post-surcharge head loss coefficient was around 0.45; which was more than 30% increase than the normal condition. In both cases, the threshold surcharge remained around 20% of the manhole diameter, which was equivalent to the straight pipe scenario.

On the other hand, at the bending angles of 170° and 165° cases, the threshold surcharge was found to increase up to 33% of the manhole diameter, which was around 50% increase compared to the normal condition. The maximum head loss coefficient was seen at a 0.50\(\Phi_p\) surcharge and found in the range of 1.15 in both cases. The head loss became consistent at surcharges more than 1.50\(\Phi_p\). At post-threshold surcharge scenario, the head loss at 170° bend was found to be around 0.6; which was an almost 75% rise compared to the straight pipe case. A further 5° increase in the bending angle accelerated the changes further. At 165° bend post-threshold surcharge condition, the head loss coefficient became around 0.75; which was a 25% rise compared to 170° bend case and was almost doubled to that of the straight pipe scenario. At pre-threshold surcharge condition, the maximum head loss coefficient at both 170° and 165° bend pipe.
Head loss coefficients due to pipe bending: $K$ vs $s/\Phi_p$

**178° bending**

- 30 lps
- 60 lps
- 90 lps
- 120 lps
- $s/\Phi_p = 0.06$
- $s/\Phi_p = 0.20$
- $s/\Phi_p = 0.33$

**175° bending**

- 30 lps
- 60 lps
- 90 lps
- 120 lps
- $s/\Phi_p = 0.06$
- $s/\Phi_p = 0.20$
- $s/\Phi_p = 0.33$

**170° bending**

- 30 lps
- 60 lps
- 90 lps
- 120 lps
- $s/\Phi_p = 0.06$
- $s/\Phi_p = 0.20$
- $s/\Phi_p = 0.33$

**165° bending**

- 30 lps
- 60 lps
- 90 lps
- 120 lps
- $s/\Phi_p = 0.06$
- $s/\Phi_p = 0.20$
- $s/\Phi_p = 0.33$

Figure 7. Manhole head loss coefficients for different horizontal angle differences between inlet and outlet.

conditions was found 1.25 which was 80% higher compared to a straight pipe manhole.

### 4.4. Effect of the manhole to pipe ratios

The change of head loss coefficients due to variable $\Phi_m/\Phi_p$ at different surcharges is shown in Figure 8. At this figure, the x-axis indicates the surcharges as a ratio of the corresponding manhole diameters. In general, the manhole head loss coefficients increased with the increase in the manhole to pipe ratios. However, to explain the trend of manhole hydraulics, the manhole sizes are divided into three categories: small manholes with $\Phi_m/\Phi_p \leq 3.0$, medium manholes with $3.0 < \Phi_m/\Phi_p < 4.5$ and large manholes with $\Phi_m/\Phi_p \geq 4.5$.

For all manholes considering $\Phi_m/\Phi_p < 3.0$, the flow from the inlet pipe passed through the outlet making comparably less head loss at all the surcharge conditions. Such manholes can maintain drainage conditions without much loss of energy/energy dissipation, indicating a better drainage performance. At $\Phi_m/\Phi_p = 1.5$, the head loss coefficients ranged from 0.21 at a low surcharge to 0.17 at high surcharge condition. With the increase in $\Phi_m/\Phi_p$ and up to $\Phi_m/\Phi_p = 3.0$, the head loss increased at all the surcharge ratio conditions. At $\Phi_m/\Phi_p = 3.0$, the head loss on the

Figure 8. Effect of head loss on manhole to pipe ratios.
manhole ranged between 0.4 and 0.6. These manhole models did not show any indication of having threshold surcharge. The hydraulic regime changed between $\Phi_m/\Phi_p$ of 3.0 and 3.1. At $\Phi_m/\Phi_p = 3.1$ manhole, the head loss decreased sharply at all surcharges. In this case, the head loss coefficient showed high value at low surcharge until the surcharge condition reaches around 0.2$\Phi_m$ (equivalent to 0.62$\Phi_p$). At higher surcharge than this value, the manhole head loss reduces. This phenomenon can be seen to all medium manholes with $3.1 < \Phi_m/\Phi_p < 4.0$. Another change in the head loss characteristic was observed between $\Phi_m/\Phi_p$ of 4.0 and 4.5. When $\Phi_m/\Phi_p \geq 4.5$, the manhole showed a very high head loss coefficients at all surcharge conditions.

The hydraulic behaviors at different manhole sizes are further explained in Figure 9, which shows the jet flow at the vertical section of different manholes. As the flow traveled through all the manholes, the jet core region became narrower. Theoretically, this change happens at a ratio of 1:6.2 towards the manhole travel length (Albertson et al. 1950). This change indicates that at a manhole with an inlet pipe diameter of 0.3 m, the core jet would travel $(6.2 \times 0.3 =) 1.86$ m before it diminishes completely. This ratio also suggests that for any manhole with $\Phi_m/\Phi_p < 6.2$, the jet core would not dissipate in the manhole, instead would pass through the outlet. Figure 9 indicates a deviation from that theoretical condition, showing that the core jet flow zone became too weak at $\Phi_m/\Phi_p = 4.5$ and diminished within the manhole. At the small manholes (small $\Phi_m$), the fast-moving jet flow did not change its shape, and the core jet remained strong enough when it reached the outlet pipe. At large manholes, especially at $\Phi_m/\Phi_p > 4.5$, the jet core dissipated and became too weak before it reached the outlet, which induces an oscillation in the manhole. Due to the oscillation, these manholes showed characteristics

![Figure 9](image-url)
similar to those of below threshold surcharge regions at surcharge ratios $s/\alpha \leq 0.55$. The oscillation also created irregular high and low head loss coefficients as the surcharge increased. Both oscillation and irregular behavior of head loss coefficients were also reported by Guymer et al. (2005) and Stovin, Bennett, and Guymer (2013) while investigating Type B scaled manhole using a laboratory experiment and CFD modeling, respectively.

At small manholes, the core region remained strong enough until the outlet as such the diffusion region could not influence the core jet and hence the head loss of the manhole did not change much. At medium manholes ($3.0<\alpha<4.5$) with lower surcharge (at around $s/\alpha<0.2$), the diffusion region hit the water surface and created an oscillation in the flow. For this reason, the core zone could not enter the outlet smoothly, which created an additional head loss.

All findings of the study are summarized in Table 3.

### Table 3. Summary of the results.

| Manhole Types | Inlet orientations | Examined manhole to pipe ratio (-) | Surcharge ratio, $\alpha$ | Head loss coefficients, $K$ (-) | Comments on $K$ |
|---------------|-------------------|-----------------------------------|---------------------------|--------------------------|----------------|
| Type A        | 180°              | 1.5-3.0                           | $0<s/\alpha<0.2$         | 0.2-0.5                  | Increases as manhole to pipe ratio increases. No effect on surcharge |
|               |                   |                                   | $s/\alpha>0.2$           | 0.3-0.9                  | Very low value at low surcharge, around 0.3-0.4 at surcharge ratio of 0.2, higher values in between |
|               |                   |                                   | $s/\alpha>0.2$           | 0.3-0.4                  | Steady value with increase of surcharge, increases if manhole ratio increases |
|               |                   |                                   | $s/\alpha>0.2$           | 0.4-1.2                  | Varies irregularly, mainly high at low surcharge and lowers with high surcharge |
| Type B        | 180°              | 3.3                               | $0<s/\alpha<0.2$         | 0.3-0.8                  | Around 0.3 at low surcharge, around 0.35 at surcharge ratio of 0.2, higher values in between |
|               |                   |                                   | $s/\alpha>0.2$           | 0.35-1.0                 | Around 0.35 at low surcharge, around 0.45 at surcharge ratio of 0.2, higher values in between |
|               |                   |                                   | $s/\alpha>0.2$           | 0.45                     | Remains steady as surcharge increases |
|               |                   |                                   | $s/\alpha>0.3$           | 0.6                      | Remains steady as surcharge increases |
|               |                   |                                   | $s/\alpha>0.3$           | 0.75                     | Remains steady as surcharge increases |
| Type C        | 180°              | 3.3                               | $0<s/\alpha<0.2$         | 0.3-0.8                  | Very low value at low surcharge, around 0.3 at surcharge ratio of 0.2, higher values in between |
|               |                   |                                   | $s/\alpha>0.2$           | 0.3                      | Steady value with increase of surcharge |
|               |                   |                                   | $s/\alpha>0.33$          | 0.1-0.3                  | Very low value at low surcharge, around 0.1 at surcharge ratio of 0.33, higher values in between |

5. Conclusions

The work presented in this study compares surcharge manhole hydraulics and head loss coefficients due to various changes in their properties. The manholes were modeled numerically using open source CFD modeling tools OpenFOAM® with the interFoam solver. Three different types of surcharged manholes molds were tested: Type A, with no guided channel and a sump zone below the inlet-outlet pipe invert level; Type B, similar to Type A but without sump and Type C with a U-shaped invert guided channel at the manhole floor. All three manholes were prototype scaled having manhole to pipe diameter ratio equal to 3.33. Each manhole showed variation in head loss coefficients due to change of surcharge levels. Type A and B manhole had threshold surcharges approximately as 20% of the manhole diameter; whereas, for Type C manhole, it was as high as 33%.

All the three manholes showed higher head loss coefficients at surcharge conditions lower than threshold surcharge level. For any inflow and surcharge condition, manhole Type C was found to be most hydraulically efficient as it showed the lowest head loss coefficients at all inflow and surcharge conditions.

The effect of pipe bending in the manhole connection showed two different characteristics according to the bending angles. At bending angles $175^° \leq \alpha < 180^°$, the jet flow core region could dissipate through the outlet pipe and created a very small increase in the post threshold head loss coefficient. The changes in the pre-threshold head loss were insignificant. At bending angles $\alpha \leq 170^°$, the core jet flow disappeared in the manhole and created comparably higher threshold surcharge. These bend conditions created higher head loss coefficients at both pre and post-threshold surcharge.
Analysis of effects due to manhole to pipe diameter ratios showed three different hydraulic regimes. For Φ_m/Φ_p<3.0, the head loss did not show any susceptibility to the available surcharge. All manholes with 3.1< Φ_m/Φ_p < 4.0 showed a distinctive threshold surcharge which is around 20% of the Φ_m. The head loss is found significantly higher at surcharge below this threshold. For manholes with Φ_m/Φ_p≥4.5, the jet flow from the inlet became too weak when it reaches the outlet and created high head loss at all surcharges.

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