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LITERATURE REVIEW OF ENERGY LOSSES IN MANHOLES

by

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Preface

The subject of my planned thesis for the degree of Technical Licentiate is "Three-dimensional numerical modelling of energy losses in a manhole". The purpose of this literature study was to get an overview over research concerning energy losses in manholes and to gather background material for the numerical study. Supervisors are Professor Lars Bergdahl and Associate Professor Sven Lyngfelt.

Göteborg, December 1995

Martin Asztély

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1. Introduction

Computer models for the analysis of water and pollution transport in pipe networks are based on the theory of one-dimensional flow. In normal applications such models give an appropriate description of the course of transportation of a particular system. The flow in local points such as manholes, weirs, compensation basins and junctions is, however of pronounced three-dimensional character, and is necessarily very simplified in these models.

Under surcharged conditions the energy losses at for example manholes may be crucial for the pressure level in a sewer system. For a risk analysis of basement flooding and discharge estimates of overflows it is therefore of practical interest to increase the knowledge of the flow in these local points. The present study is concentrated on manholes. Knowledge of energy losses for each type of manhole must be input to the simulation programs.

Previous contributions to the understanding of the energy loss in manholes have come about mainly through laboratory experiments. In several studies observations have been made of energy losses and flow conditions at various geometry's. Basic considerations are given in Chapter 3 and relevant investigations are referred in Chapter 5. In the 1990's two different models of energy loss in manholes have been presented. The first considers a submerged jet at the inlet of the manhole and is based on an analytical model. The model is discussed in Chapter 4 and 6. The second model uses the principle of momentum conservation in the manhole. The model was presented by Ball (1993). His work does not consider surcharged conditions and will for this reason not be referred here. Other studies on flow in manholes not reviewed are Ball (1985, 1988, 1991), Watanebe and Kurihara (1993), Kusada et. al. (1993).

2. Manholes

The main reason for using manholes is to have points in the pipe network where inspection and rinsing of the pipes are possible. There are several different shapes of manholes (see Fig. 2.1). Rectangular manholes are very common in the USA where heavy rainflow enters the system, through the top of the manhole. In Europe circular manholes are more common.
The most common types are designed as one pipe in - on pipe out, and two pipes in - one pipe out systems, often with different diameters.

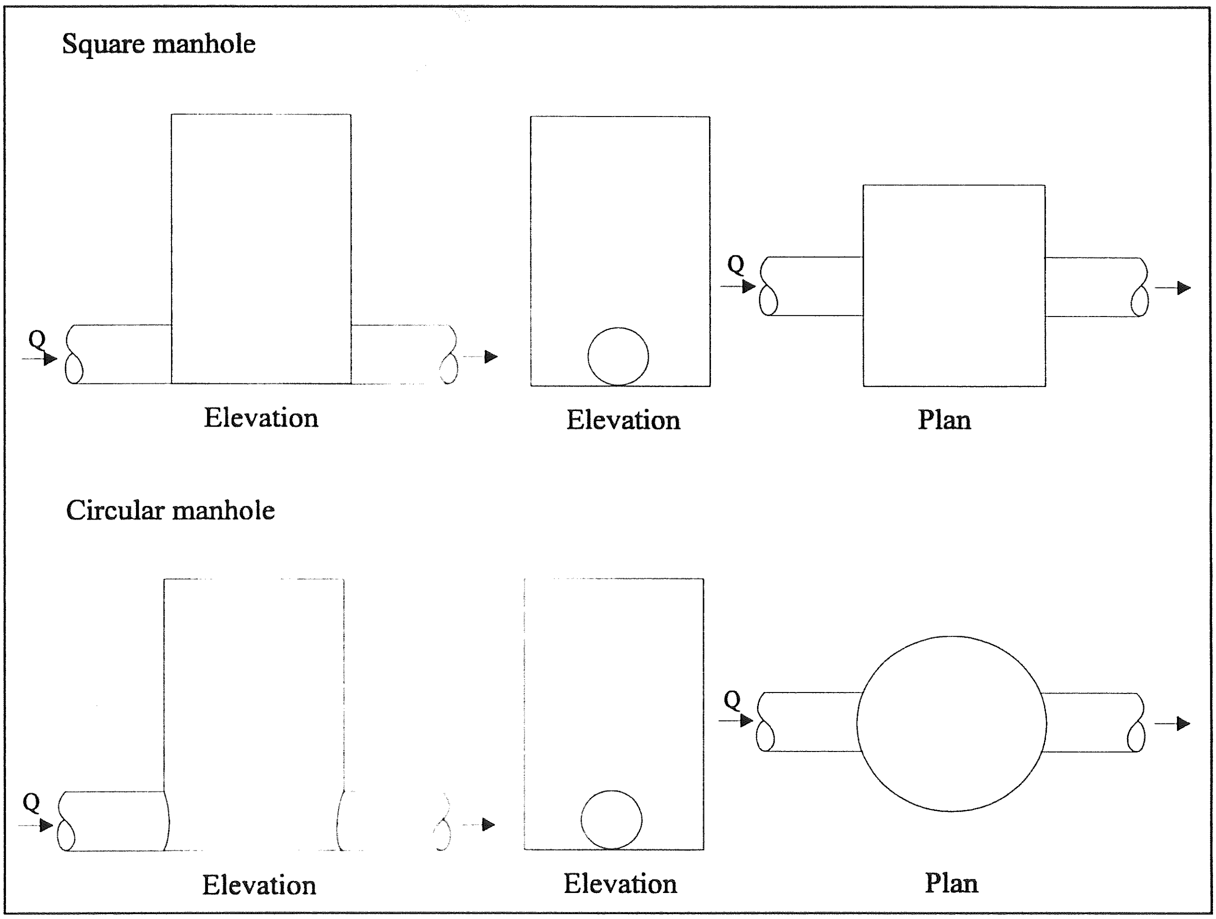


Figure 2.1 Sketches of square and circular manholes

The circular manhole is often seen with the lower half of the pipe extended through the manhole and with horizontal benches added extending from the semicircular channel to the walls of the manhole, see Fig. 2.2-2.3

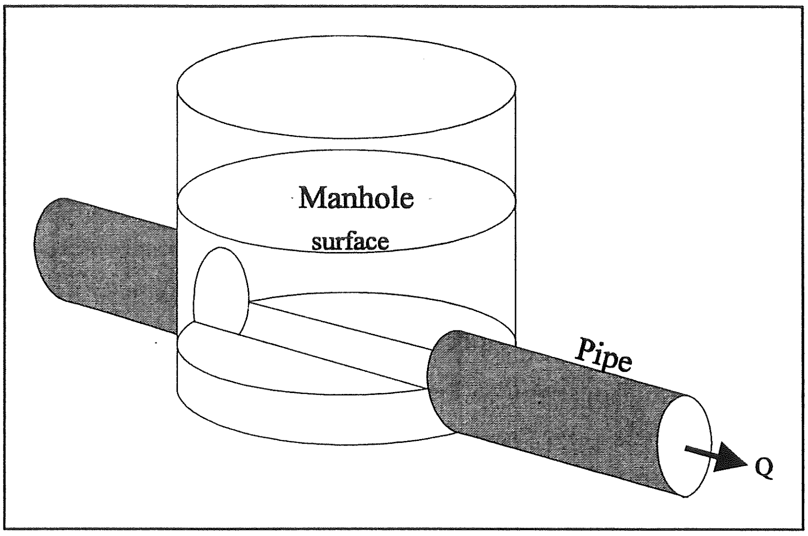


Figure 2.2 Sketch of a manhole (surcharged condition)

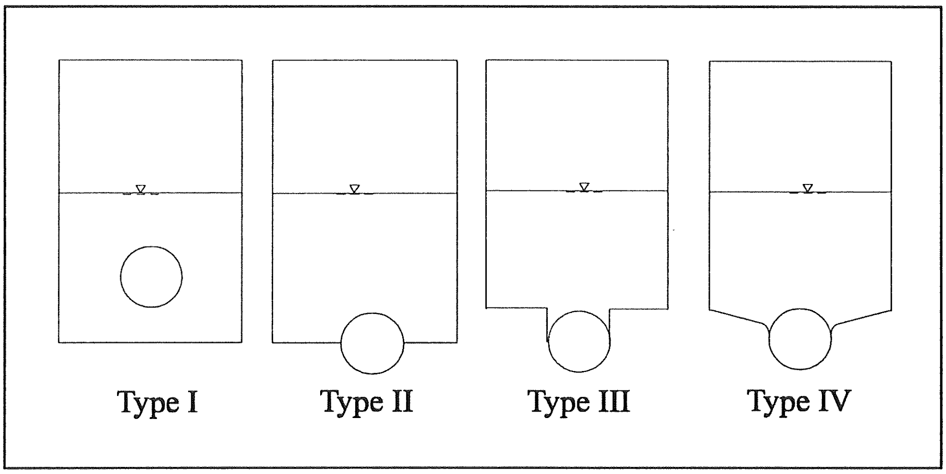


Figure 2.3 Elevations of typical manholes (surcharged condition)

When water runs through a pipe, energy losses caused by friction against the wall of the pipe occur. If the pipe is only partly filled energy losses are increased by surface waves (Marsalek 1981). Energy losses in a manhole are caused by for instance

- **The retardation of the fluid just upstream the entrance (in partly filled pipes).**
- **Sudden expansion of the flow at the entrance.**
- **Secondary flow in the manhole.**
- **Resonance oscillations in the manhole.**
- **The acceleration of the fluid at the outlet.**

The energy losses in pipes are very well understood, while the energy losses in the manholes are less well understood. The latter losses are of interest because they may have significant effect on the capacity of the pipe network. The geometric shape of a manhole determines its loss coefficients.

3. Measurement of energy losses

The complex flow pattern in manholes which includes effects of retardation, acceleration, rotation in different planes and flow interference, makes it impossible to formulate a general theory for the energy losses. The attempts that have been made (for example, impulse consideration) are too imprecise to be used in computer programs without empirical confirmations, which makes it necessary to examine the geometry of each manhole separately.

One approach to estimating the energy loss of a manhole is to use the energy grade lines of the pipes on both sides of the manhole. The energy grade lines are extrapolated to the middle of the manhole and one can then measure the energy loss as the height difference between the lines in the middle of the manhole, see Fig. 3.1.

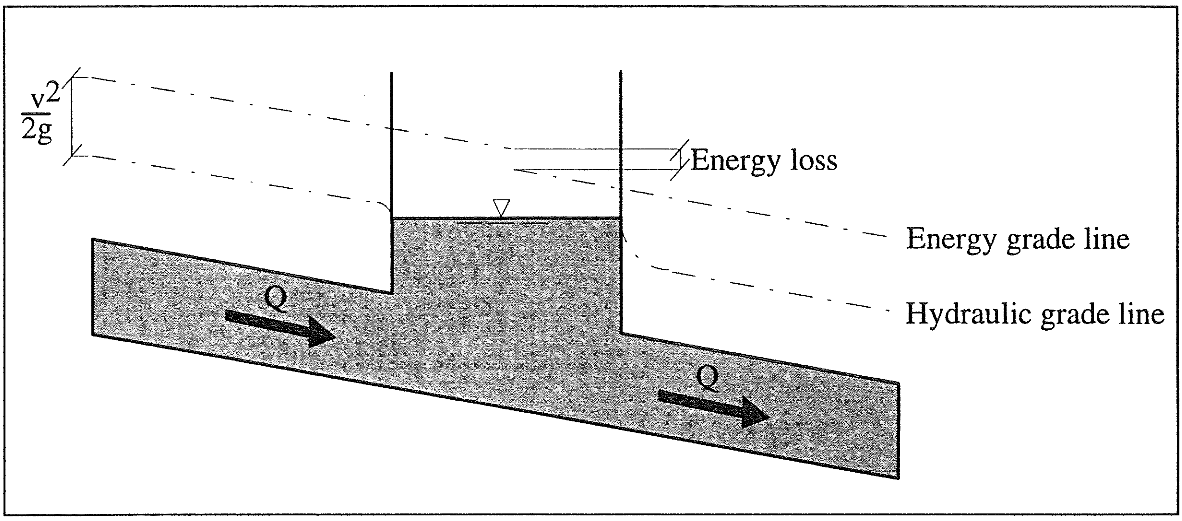


Figure 3.1 Pressurised flow with associated energy grade lines and hydraulic grade lines.

There is often a difference in pipe diameter between the entrance and the outlet of the manhole thus the velocity head becomes different. In spite of this the hydraulic grade line is commonly used in simulation programs. Since the energy loss is proportional to the velocity head according to Eq 3.1, one may describe a manhole-energy loss in terms of an energy loss coefficient according to Eq 3.2

$$\Delta E = K\frac{v_d^2}{2g} \qquad \text{... (3.1)}$$

$$K = \Delta E \frac{2g}{v_d^2} \qquad \text{... (3.2)}$$

where v_d is the velocity defined as the flow divided by the pipe area.

In experiments it has been found that the energy loss coefficient in the manhole depends on the water depth (y) and the ratio of the manhole diameter (D_m) to the pipe diameter (D). Figure 3.2 shows an example of the energy-loss coefficient as a function of y/D in a manhole of type II.

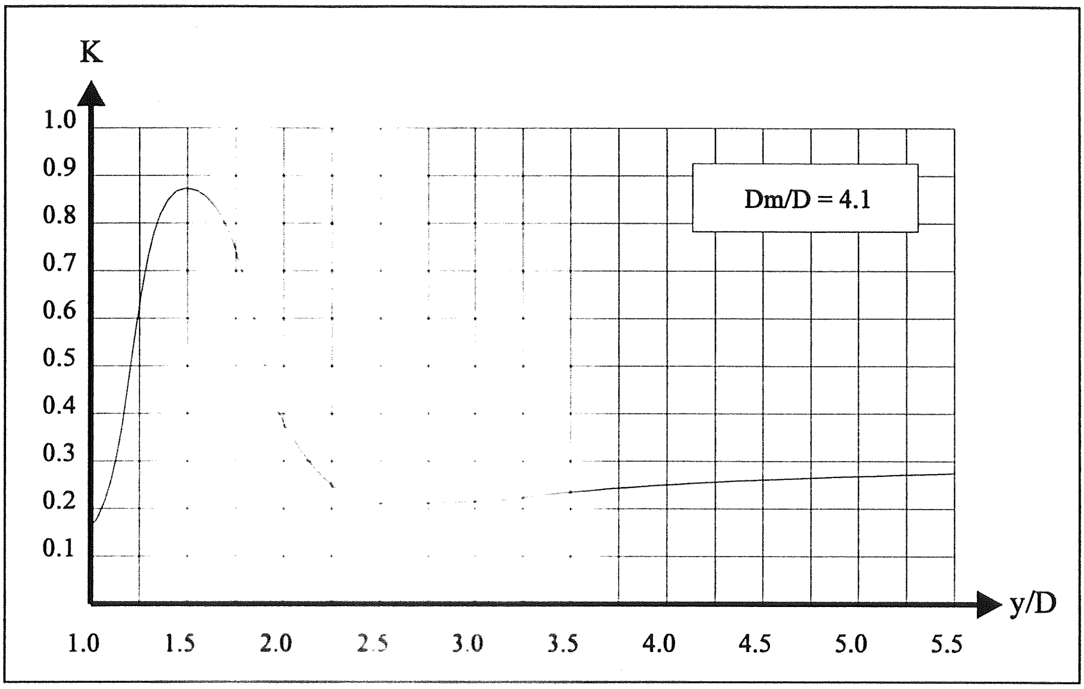


Figure 3.2 An example of energy loss coefficient as a function of y/D (Manhole type II) [after G. Lindvall 1986].

The energy loss coefficient is then used in the energy equation. Considering the upstream (u) and downstream (d) section of the manhole one obtains, Eq. 3.3

$$z_u + y_u + \frac{\alpha_u v_u^2}{2g} = z_d + y_d + \frac{\alpha_d v_d^2}{2g} + K\frac{v_d^2}{2g} \qquad \text{... (3.3)}$$

where v_d and v_u are the mean velocities in each pipe, z is the elevation, y the depth of the flow, g is the gravitational acceleration and α is the kinematic energy coefficient.

4. Submerged jet theory

An approach to calculating the energy loss is to consider a submerged jet in the manhole. In this approach one divides the flow into entrance flow and exit flow as Pedersen and Mark (1990) explain very clearly:

"**Entrance**

Inspection of the flow pattern in a circular manhole has revealed that the inflowing water behaves like a submerged jet, which entrains water from the ambient fluid and increases the streamwise discharge through the manhole (see Fig. 4.1). During steady state conditions, the outflow from the manhole equals the inflow, and hence the surplus discharge is rejected from the main flow before it leaves the manhole. The entrained water is accelerated on account of the kinetic energy of the through-flowing water, and similarly is the energy of the surplus discharge lost in the manhole as well. The energy transformation in this persistent pumping mechanism is directly related to the entrance head loss in the manhole." By use of a simple jet theory for submerged jets one can evaluate this entrance head loss by calculating the ratio of the energy flux before to that after the entrance of the manhole.

"**The Exit**

At the outlet from the manhole, the water is accelerated through a vena contracta in the outlet pipe, and hence an ordinary expansion loss is encountered downstream the vena contracta.

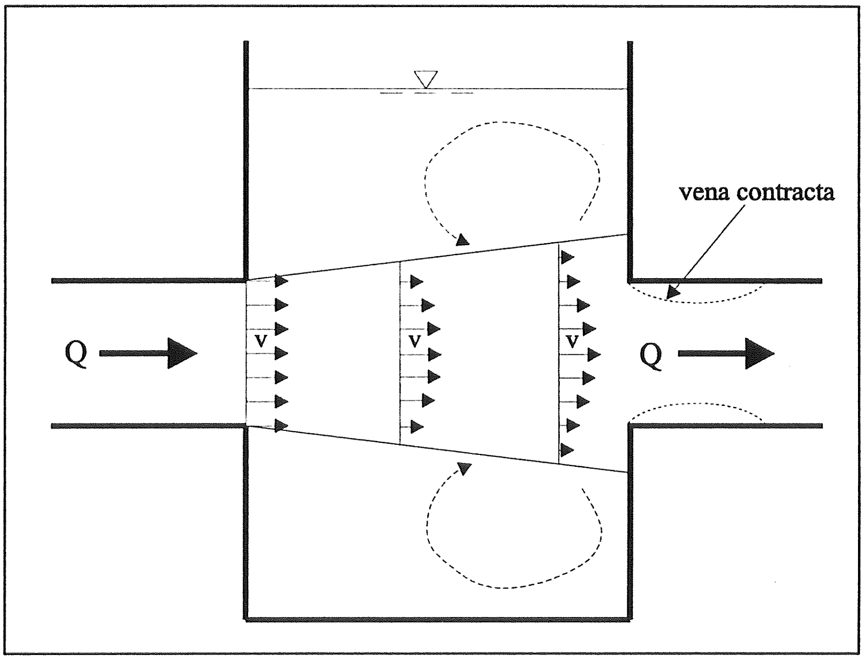


Figure 4.1 Velocity distribution of a jet in the manhole

This head loss is calculated by use of the Carnot loss combined with an experimentally determined contraction coefficient Ψ, see Eq. 4.1. The coefficient Ψ is nearly constant (around 0.6-0.7) with a weak dependency on the effective flow area in the manhole. The latter has been determined as the area in the jet that has an integrated discharge of Q." The contraction loss caused by the vena contracta is;

$$\Delta E_{exit} = \left[c + \left(\frac{1}{\Psi} - 1 \right)^2 \right] \frac{v_d^2}{2g} \qquad \text{... (4.1)}$$

The coefficient c is a non dimensional parameter that is dependent of the Reynolds number and v_d is the velocity defined as the flow divided by the pipe area. One may describe the energy loss coefficient according to Eq. 3.1. The loss coefficient is split into entrance and exit coefficients, see Eq. 4.2

$$K = K_{entr} + K_{exit} \qquad \text{... (4.2)}$$

The entrance coefficient originates from the submerged jet and the exit coefficient from the expansion downstream of the vena contracta. This energy loss coefficient is then used in the energy equation, see Eq. 3.3. It should be noticed that this method is only valid for large water depths ($y / D_m > 2$) since the jet theory demands that the flow is unaffected by secondary flow. Possibly, one might apply this theory for other shapes than the one in Figure 4.1 for instance by using the theory of a half jet for the type II and IV manholes and two-dimensional theory for the type III manhole.

5. Publications on measurements of energy losses

Some of the most important investigations of energy losses in manholes are presented in chronological order below:

5.1 W.M. Sangster et. al. (1958)

In 1958 Sangster et. al. published an article on flow through junctions and manholes. The study only covered a type of manhole similar type I where the invert of the pipe is flush with the bottom of the manhole. The depth was larger than twice the downstream pipe diameter at all measurements. The study covered a large amount of measurements and made it possible to produce tables that are used today throughout the world. The examined parameters are presented in Table 5.1. In the study, they measured the pressure level along the pipes which meant that they obtained pressure loss instead of energy loss when they extrapolated the hydraulic grade line to the middle of the manhole. It is therefore very important to keep in mind that these measured pressure losses are not to be used as energy losses.

In the simplest case where only straight-through flow is considered and the ratio of the diameter of the downstream pipe to the upstream pipe is 1.2, the coefficients are 0.91 and 0.95 for a manhole with the connection between the pipe and the manhole rounded and sharp respectively. If these are calculated as energy loss coefficients the corresponding values are 0.12 and 0.16 which means a much larger relative difference.

There is no result that shows the fact that losses vary with the water level in the manholes. However, there is a comment stating that in the case of straight-through flow, small and unsystematic variations of the loss coefficient can be observed. The reason could be the use of very small manholes in the study (circular: 1.05D-1.27D, quadratic: 1.05D-2.10D). According to Lindvall (1984) the phenomenon is more pronounced for larger manhole diameters.

Table 5.1 Parameters examined by Sangster et. al.

Examined parameter	Sangster et. al. 1958
Type of manhole	I[3]
Part-full pipes	-
Totally filled pipes	X
Straight-through flow	X
Connected side pipe	X[2]
Varying diameter of pipe	X
Varying diameter of c.s.p[1]	X
Varying diameter of manhole	X
Rectangular manhole	X
Circular manhole	X
Varying drop in manhole	X
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

[1] *Connected side pipe*

[2] *Plus inflow through the top of the manhole*

[3] *Lower part of the pipe flush with the bottom of the manhole*

5.2 P. Ackers (1959)

Ackers (1959) studied the flow in open invert manholes with straight-through flow and compared it with the flow in manholes with steel hatch boxes. It was found that the hatch box did not yield any significant reduction of resistance, except under surcharged conditions. The head losses at open invert manholes are small, except when surcharge occurs. However if the manhole contains a bend and sewer velocities are high, the head loss under surcharge may be considerable. He also investigated whether there was a difference between brick-on-edge benching and concrete benching and found that there only was a small difference, as far as manhole head loss is concerned.

Table 5.2 Parameters examined by Ackers

Examined parameter	Ackers 1976
Type of manhole	IV[2]
Part-full pipes	X
Totally filled pipes	X
Straight-through flow	X
Connected side pipe	-
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	-
Varying drop in manhole	-
Bend of the main pipe	X
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

[1] *Connected side pipe*

[2] *With a benching of 1D + Hatch boxes.*

5.3 V. Yevjevich and A.H. Barnes (1970)

In 1970 Vujica Yevjevich and A.H. Barnes published a series called "Flood routing through storm drains," part 1-4 covering:

1. Solution of unsteady free surface flow in storm drains.
2. Physical facilities and experiments.
3. Evaluation of geometric and hydraulic parameters.
4. Numerical computer methods of solution.

Here only part 2-3 will be commented since part 1 and 4 cover other subjects.

In the study a full scale experimental set-up was built in order to investigate non-stationary flow in part-full pipes with a manhole. As a part of the study a model set-up of scale 1:5.6 was also built in order to investigate the effects of a connected side pipe (90°). The side pipe was connected both in an upper and a lower position. The main pipe was part-filled for all cases but the connected side pipe was both filled and part-full for different cases. The studied parameters examined are presented in Table 5.3.

With the energy grade line known the power loss was calculated. The parameter P_r was defined as, Eq. 5.1.

$$P_r = \frac{\text{incoming power - outgoing power}}{\text{incoming power}} \qquad \text{... (5.1)}$$

Expressions for manholes with a connected side pipe were derived according to Eq. 5.2, which is valid for the case with the side pipe connected in the upper position, and 5.3 for the side pipe in the lower position

$$(P_r - 0.77)(Q_r + 0.55) = -0.482 \qquad \text{... (5.2)}$$

$$P_r = \frac{-2.78 + 1.71D_r}{Q_r + 3.122 - 0.167D_r} + 0.77 \qquad \text{... (5.3)}$$

where the parameter Q_r is the ratio of the lateral flow to the upstream flow and D_r is the ratio of the water depth to the diameter of the upstream pipe. The equations are valid for a specific manhole. One interesting fact is that the energy loss is less for the case with the side pipe connected to the lower position than the case with the pipe connected to the upper position. This power loss is converted into energy loss with Eq. 5.4,

$$E = \frac{P}{\gamma Q} \qquad \text{... (5.4)}$$

where Q is the volume rate of flow in cubic feet per second, γ is the specific weight of water in pounds per cubic feet and P is foot-pound per second.

Table 5.3 Parameters examined by Yevjevich and Barnes

Examined parameter	Yevjevich & Barnes 1970
Type of manhole	II
Part-full pipes	X
Totally filled pipes	-
Straight-through flow	-
Connected side pipe	X[2]
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	-
Varying drop in manhole	-
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	-

[1] *Connected side pipe*

[2] *Including varying drop of the c.s.p. (two different)*

5.4 H. Liebmann (1970)

In 1970 Horst Liebmann made a study on straight-through flow in circular manholes. The studied parameters are presented in Table 5.4. A type IV manhole was used with four different benching levels.

One interesting result from Liebmann´s investigation is that for an interval of water depth in the manhole of approximately 1D to 1.5D (D is the diameter of the pipes) the energy loss increases considerably. This phenomenon was observed by Lindvall (1986) too, see
Figure 3.2. The increase was smaller for a deeper benching and seems to be caused by surface oscillations.

Table 5.4 Parameters examined by Liebmann

Examined parameter	Liebmann 1970
Type of manhole	IV[2]
Part-full pipes	X
Totally filled pipes	X
Straight-through flow	X
Connected side pipe	-
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	-
Circular manhole	X
Varying drop in manhole	-
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

[1] *Connected side pipe*

[2] *Type IV with four different benching levels*

5.5 J.R. Prins and D.R. Townsend (1976)

In 1976 J.R. Prins and D.R. Townsend made a study with the purpose of investigating partly filled pipes to find a suitable manhole design to minimise the energy losses. For example, a guide screen was installed but experiments showed that benching in the manhole was more effective to decrease the energy loss. The examined parameters are presented in Table 5.5.

The pipes used in the experimental set-up were very short. The downstream length was 18D and the upstream was 43.3D. Even the length of the connected side pipe is possibly too small ($55D_S$, D_S is the side pipe diameter). Some of the results are disputable since they show that the energy loss in both the upstream and the side pipe is decreasing with increasing side flow. The most important result in the report is that the benching decreases the energy loss.

Table 5.5 Parameters examined by Prins and Townsend

Examined parameter	Prins & Townsen d 1976
Type of manhole	II,III
Part-full pipes	X
Totally filled pipes	-
Straight-through flow	-
Connected side pipe	X
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	-
Varying drop in manhole	X[2]
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	X
Varying water depth in manhole	X

[1] *Connected side pipe*

[2] *and drop in c.s.p*

5.6 B. Archer, R. Bettes and P.J. Colyer (1978)

In 1978 F. Bettes, B. Archer and P.J. Colyer published a laboratory report on manholes at Sunderland Polytechnic. Later the same year they published another report on the same experiments. The study covers totally filled pipes with the same diameter of the pipes upstream and downstream and both 30° and 60° bends in the manhole, see Figure 5.1.

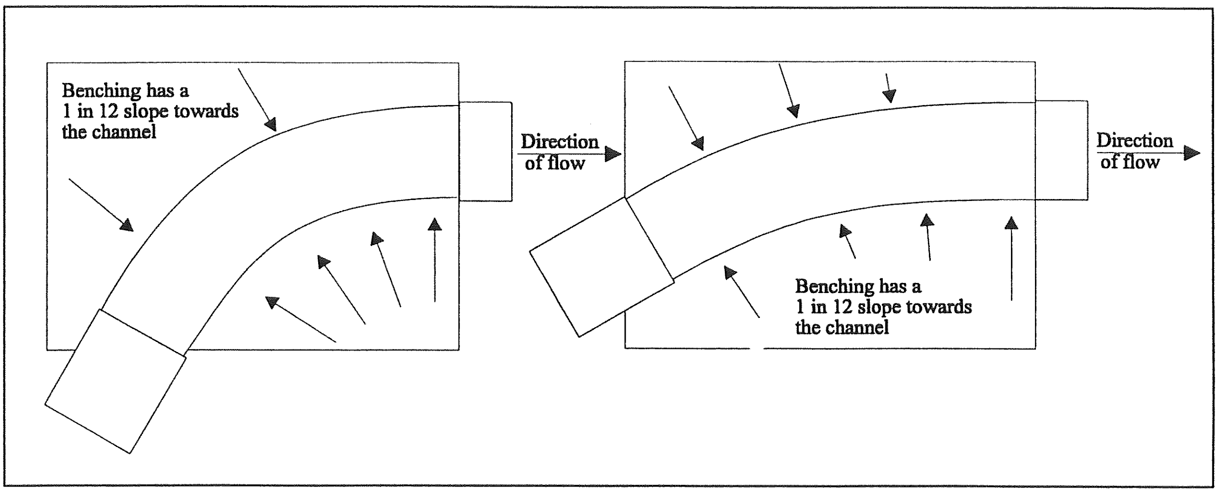


Figure 5.1 Quadratic manholes with a 60° and 30° bend.

Both quadratic and circular manholes were included in the study. Two different inclinations of the pipes were used.

The authors observed distinct disturbances between the water depth of 1D to 1.5D in the manhole (D is the pipe diameter). They considered that the disturbances which caused a slight increase in energy loss, were negligible. Still, the observed increase is larger than the increase observed by Liebmann (1970). No other study of energy losses with a bend in a manhole was found in the litteraure.The main conclusion is; the smaller the radius of the bend the less influence the water depth has upon the energy loss.

Table 5.6 Parameters examined by Archer et. al.

Examined parameter	Archer et. al. 1976
Type of manhole	IV
Part-full pipes	-
Totally filled pipes	X
Straight-through flow	X
Connected side pipe	-
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	X
Varying drop in manhole	-
Bend of the main pipe	X
Varying inclination of main pipe	X
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

[1] *Connected side pipe*

5.7 C.M. Hare (1980-1983)

Clive Hare published his master thesis in 1980 where he presented equations for loss coefficients for junctions based on certain simplifying assumptions. Three years later he published an article about junction pits which may be compared with manholes since they have the same characteristics. He presented loss coefficients for junction pits with one incoming and one outgoing pipe with different bends (0°-90°). For further details about the experiments see Table 5.7.

Table 5.7 Parameters examined by Hare

Examined parameter	Hare 1984
Type of manhole	I
Part-full pipes	-
Totally filled pipes	X
Straight-through flow	X[2]
Connected side pipe	-
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	-
Varying drop in manhole	-
Bend of the main pipe	X
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	-

[1] *Connected side pipe*

[2] *With different angles of the in- and out flow*

5.8 D.A. Howarth and A.J. Saul (1984)

This study is focusing upon the on the influence of unsteady flow on energy loss coefficients in comparison with steady flow. In the tests discharge-time hydrographs were used based on the 50 and 90 percentile peakedness summer storm profiles outlined in the flood studies report [Natural environmental research council 1975]. The study covered type IV manholes plus one manhole that was of type IV but with a slightly different configuration, see Figure 5.2. For further details about examined parameters see Table 5.8.

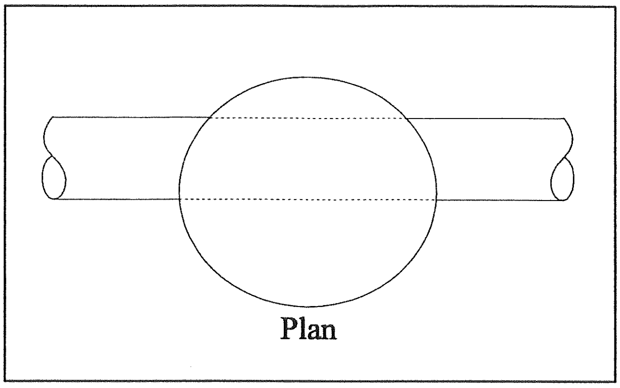


Figure 5.2 Circular manhole with an eccentrically placed pipe.

Here some important results are quoted. "The results of the work showed that, as expected, each manhole arrangement caused no noticeable lag or attenuation of the discharge-time hydrograph" and "the shape of the flow hydrograph was found not to influence the magnitude of the loss coefficient but at low flowrates significant variations in the loss coefficient were observed between the steady flow and unsteady flow tests". Furthermore the results showed the important fact that the dimensionless ratio of surcharge depth to the manhole diameter was of considerable importance to the energy loss. Circular swirling motion of the flow in the manhole that resulted in a very high energy loss coefficient was observed. As the author writes, "As these losses may be several times greater than those usually taken for manholes, it may be concluded that when a storm hydrograph is discharged through a pipe network or a sewerage system in which surcharge occurs, the estimation of total energy loss may seriously be in error."

Table 5.8 Parameters examined by Howarth and Saul

Examined parameter	Howarth & Saul 1984
Type of manhole	IV[2]
Part-full pipes	-
Totally filled pipes	X
Straight-through flow	X
Connected side pipe	-
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	X
Varying drop in manhole	-
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

[1] *Connected side pipe*

[2] *For different depth of the benching*

5.9 J. Marsalek (1981-1987)

The first study (Marsalek 1981) is similar to the study by Liebmann (1970). It covers straight through flow with the same diameter of the in- and out-flow pipes. The study included one manhole of type III with square shaped benching. The examined parameters are presented in Table 5.9. There is nothing in the report that indicates that the surface oscillation observed by Liebmann (1970) occurs. This is probably due to the small diameters (compared to Liebman) used in the study. In 1984 he published some more experiments and some corrections to the loss coefficients. In 1985 Dick and Marselek made a review on recent data on head losses at sewer manholes and used the gathered data in a program that calculates the flow routing in surcharged sewer systems, but the computer model does not allow an explicit consideration of junction head loss. Therefore they used an equivalent pipe roughness that also was proposed by Liebmann (1970). 1987 Marsalek presented an article about junctions with two opposed lateral sewers, see Figure 5.3.

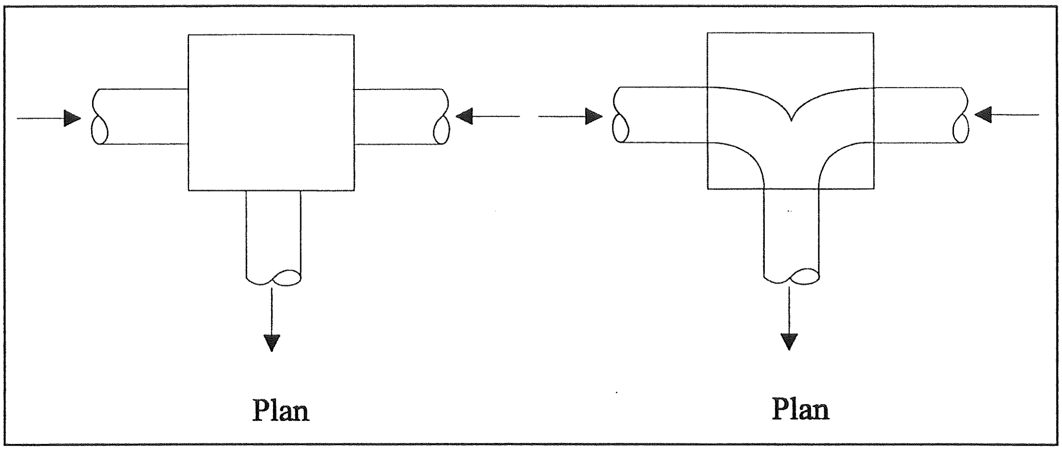


Figure 5.3 Junctions with two opposed lateral sewers.

The results of this investigation were that head losses at a junction of two opposed laterals are affected by both the junction geometry and the relative discharge $Q_r = Q_{li} / Q_O$, where Q_{li} is the flow in one of the incoming laterals and Q_O is the outgoing flow. All parameters examined in these studies are presented in Table 5.9.

Table 5.9 Parameters examined by Marsalek

examined parameter	Marsalek 1981	Marsalek 1984	Marsalek 1987
Type of manhole	I,II,III[2]	I,II,III	I,II,III
Part-full pipes	X	-	-
Totally filled pipes	X	X	X
Straight-through flow	X	X	-
Connected side pipe	-	-	X
Varying diameter of pipe	-	-	-
Varying diameter of c.s.p[1]	-	-	-
Varying diameter of manhole	X	X	-
Rectangular manhole	X	X	X
Circular manhole	X	X	-
Varying drop in manhole	-	-	-
Bend of the main pipe	-	-	X
Varying inclination of main pipe	-	-	-
Varying inclination of main c.s.p[1]	-	-	-
Varying angle of side pipe	-	-	-
Varying water depth in manhole	X	X	-

[1] *Connected side pipe*

[2] *The type III was studied with two different configurations, one ordinary and one with squared benching.*

5.10 A.J. Johnston and R.E. Volker (1990)

In 1990 Archie J. Johnston and Raymond E. Volker wrote an article in Journal of Hydraulic Engineering where they suggested a new empirical relationship for the loss coefficients for squared manholes with a connected side pipe (compare with Sangster et. al. 1958 and Hare 1983). They found that by using deflectors in the manhole they could reduce the loss coefficients. Further the conclude "Although the influences of box submergence and Froude number are not major they are nevertheless important in some flow situations."

Table 5.10 Parameters examined by Johnston and Volker

Examined parameter	Johnston & Volker 1984
Type of manhole	I,IV[2]
Part-full pipes	-
Totally filled pipes	X
Straight-through flow	X
Connected side pipe	X
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	-
Rectangular manhole	X
Circular manhole	-
Varying drop in manhole	-
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

[1] *Connected side pipe*

[2] *With two different depth of the benching*

5.11 G.C. Christodoulou (1986-1991)

Christodoulou (1986, 1987 and 1991) presented theoretical considerations and experimental results concerning the behaviour of drop manholes at supercritical flow. He studied a straight-through flow with a drop of different heights. For examined parameters see Table 5.11. In 1987 he made laboratory experiments on circular manholes with a drop with some further analysis on the energy loss characteristics. He fitted his experimental values on the loss coefficient to an expression containing a Froude number, see Eq. 5.4,

$$K = 2.36\left(\frac{\sqrt{gh}}{V_0}\right) - 0.37 \qquad \text{... (5.5)}$$

Here h is the drop height and V_0 is the inflow velocity. The example is valid for $0.25 < \sqrt{gh} / V_0 < 1.5$. In the 1991 study he added bends in the manhole and different inclinations of the pipes, and he presented new materials as well as new equations. In the experimental range $\sqrt{gh} / V_0 < 1.5$, he proposed the following empirical equation fitting to both sets of data, e.g., for straight-through flow as well as for α=90°, where α is the angle between the inflow and the outflow pipe.

$$K = 0.20 + 2.30\left(\frac{\sqrt{gh}}{V_0}\right)^{2.25} \qquad \text{... (5.6)}$$

The author writes further that since no influence of the angle φ is detected, this expression should also hold for other angles in the range $90° < \varphi < 180$.

Table 5.12 Parameters examined by Lindvall

examined parameter	Lindvall 1984	Lindvall 1986	Lindvall 1987	Lindvall 1993
Type of manhole	II,III	II,III[2]	II,III	II
Part-full pipes	-	-	-	-
Totally filled pipes	X	X	X	X
Straight-through flow	X	X	X	X
Connected side pipe	X	X	X	-
Varying diameter of pipe	-	-	-	X
Varying diameter of c.s.p[1]	X	X	X	-
Varying diameter of manhole	X	X	X	-
Rectangular manhole	-	-	-	-
Circular manhole	X	X	X	X
Varying drop in manhole	-	-	-	-
Bend of the main pipe	-	-	-	-
Varying inclination of main pipe	-	-	-	-
Varying inclination of main c.s.p[1]	-	-	-	-
Varying angle of side pipe	-	-	-	-
Varying water depth in manhole	X	X	X	X

[1] *Connected side pipe*

[2] *One ordinary manhole and one with an eccentric placed pipe.*

6. Publications on the submerged jet theory

6.1 B. Pedersen, O. Mark (1989-1990)

Ole Mark wrote his diploma thesis (Mark 1989) with Flemming Bo Pedersen as supervising professor. He investigated the energy losses in different circular manholes with the following configuration, see Fig 6.1. and examined parameters according to Table 6.1.

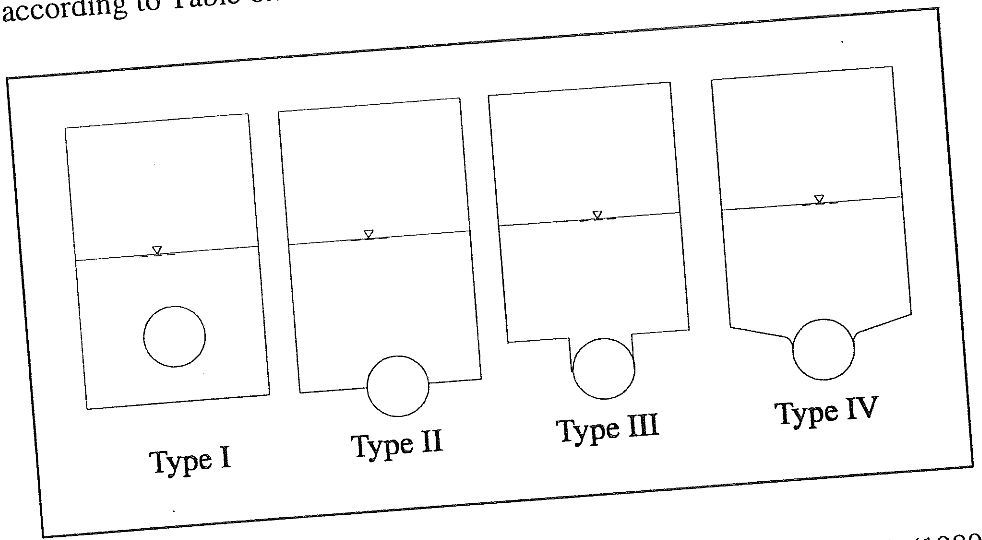


Figure 6.1 Sketch different circular manholes investigated by Mark (1989)

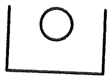
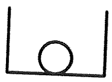
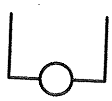
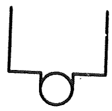
He calculated the loss coefficients for all four types but made measurement for type I and IV. For comparisons with his calculations of manhole type II and III he used measurements done by Lindvall (1986).The examined parameters are presented in Table 6.2. He found, as he put it himself "fairly good agreement" between experimental studies and theoretical calculation for depth larger than 2D, where D is the diameter if the pipe. Furthermore he found that in the experimental studies the resonance phenomena that caused the surface to oscillate, observed by Lindvall (1986) and Liebmann (1970), occurred at depth in the manholes of 1.0D to 1.5D. This oscillation caused the energy loss coefficient to increase. He also found that the jet in the manhole oscillates and it is not dependent on the surface oscillation since if a lid is put at the surface the oscillation of the jet still appears.

In 1990 Pedersen and Mark wrote an article together where they went a step further and added a simple equation for the energy loss coefficient, see Eq 6.1,

$$K = \zeta\left(\frac{D_m}{D}\right) \quad \text{... (6.1)}$$

where D_m is the diameter of the manhole. The shape factor ζ is also dependent on the type of manhole examined. As an example see table 6.1 where ζ is presented for values of $D_m<4D$.

Table 6.1 Shape factor for different types of manholes, valid for $D_m<4D$

Shape				
ζ	0.24	0.12	0.07	0.025

This equation is possible to use according to the authors since "the experiments have shown that the only governing parameter for a specific shape of a manhole is the ratio of the diameter of the manhole to the diameter of the pipe (D_m/D)". The results are only valid for high values of the ratio y/D, where y is the depth of the fluid in the manhole. For these high ratios of y/D the values of K are stabilised to constant values.

Table 6.2 Parameters examined by Mark and Pedersen

Examined parameter	Mark 1989	Pedersen & Mark 1990
Type of manholes calculated	I,II,III,IV	I,II,III
Type of manhole	I,IV	I
Part-full pipe	-	-
Totally filled pipe	X	X
Straight-through flow	X	X
Connected side pipe	-	-
Varying diameter of pipe	-	-
Varying diameter of c.s.p[1]	-	-
Varying diameter of manhole	X[2]	X
Rectangular manhole	-	-
Circular manhole	X	X
Varying drop in manhole	-	-
Bend of the main pipe	-	-
Varying inclination of main pipe	-	-
Varying inclination of main c.s.p[1]	-	-
Varying angle of side pipe	-	-
Varying water depth in manhole	X	X

[1] *Connected side pipe*

[2] *Four different type I manholes and one type IV*

6.2 B. Mugdal, B.S. Pani (1993)

In 1993 B. Mugdal and B.S. Pani wrote an article on the subject, and added studies about the effect of eccentricity between axes of the inflow and outflow pipes on the energy loss coefficient. They also determined the headloss for the case with two parallel longitudinal inflow pipes and a single outflow pipe in the manhole. They derived expressions similar to those of Pedersen and Mark (1990). In the case with a single inflow-outflow pipe arrangement their expression does not correspond to the results obtained in the experiments for depth of the manhole below approximately 2D (not commented in the article). For the case with eccentricities between the inflow and the outflow pipe axes they found that for small eccentricities the energy loss increased significantly. When the eccentricity exceeds the diameter of the inflow pipe the headloss coefficient tends to reach a limiting value of 1.5.

In the case with two inflow pipes the article does not tell whether the pipes are placed horizontally or vertically. Further it does not tell whether the flow in the two inlet pipes was equal or different. The headloss coefficient was found to increase with increased centre to centre spacing. The exit loss coefficient k_{exit} tends to reach a limiting value of 0.5 for spacing exceeding 2D.

Table 6.3 Parameters examined by Mugdal and Pani

Examined parameter	Mugdal & Pani 1993
Type of manholes calculated	I[1]
Type of manhole	I[1]
Straight-through flow	X
Connected side pipe	X[3]
Varying diameter of pipe	-
Varying diameter of c.s.p[1]	-
Varying diameter of manhole	X[2]
Rectangular manhole	-
Circular manhole	X
Varying drop in manhole	X
Bend of the main pipe	-
Varying inclination of main pipe	-
Varying inclination of main c.s.p[1]	-
Varying angle of side pipe	-
Varying water depth in manhole	X

1 *Two different types of type I was used one ordinary and one with the bottom of the pipe connected to the bottom of the manhole*

2 *Two different manholes were used.*

3 *The connected side pipe is parallel to the other inflow pipe.*

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