The role of local roughness in the hydraulic capacity of sewer pipes

M. F. Maghrebi

Civil Engineering Department, Faculty of English, Ferdowsi University of Mashhad, Iran

Abstract

The sewer conduits, which are usually made of concrete, economically should have the least of cost. This leads to the smallest diameter of pipe, which can pass the required flow rate of wastewater with an acceptable hydraulic performance. The capacity of passing the flow in pipes is affected by the roughness of the wall. On the invert of sewer pipe deposited material not only block the flow but also leads to the loss of hydraulic capacity by increasing the roughness. Corrosion of concrete in urban drainage system can be caused by the generation of hydrogen sulfide, which can be accumulated in condensation water on the soffit of the pipe. There, it is oxidized to form sulfuric acid, which can cause serious damage to pipe material. This will change the roughness of the flow and leads to a higher degree of hydraulic loss. Observations show that the most serious corruptions take place on the levels of frequently changing wastewater surface on the sides of the pipe cross section as well as the soffit. The effect of roughness particularly at the end of design period is crucial. This paper presents the result of calculation on the hydraulic capacity of sewer pipes with different local roughness along the wetted perimeter. An equivalent roughness for a certain level of wastewater based on Darcy-Weisbatch formula is computed. Next, a comparison is made between the capacity of smooth and roughened pipe. Finally, as a second approach, calculations are performed on the discharge capacity of roughened pipes by the use of equivalent roughness in Manning equation and compared with results of the first approach. It seems that Darcy-Weisbatch equation leads to a more reliable information. The results show that under moderate damage around 25% of the capacity of sewer conduits will be reduced due to this unwanted roughness.

1 Introduction

1.1 Roughness of Deposited Bed

Sediment can be found almost everywhere. Sewer sediment is any settleable particulate material that is found in the wastewater. Sediment transport influences the flow in a sewer pipe in different ways. However, we are concerned about the variation of roughness in a sewer pipe. The initial smooth wall inside a pipe is
affected by deposited material that make the hydraulic performance of the pipe different from the original smooth one. Regarding the hydraulic aspects of sediment deposition, there are two major effects: blockage and loss of hydraulic capacity. Larger and gross solids may build up, leading to partial or total blockage of the pipe. Due to blockage because of deposited materials, the cross sectional area to convey flow decreases and thus the head loss for a given discharge and depth of flow increases. The other hydraulic effect of sediment is the increase in overall resistance caused by the rough texture of the deposited bed. Deposition restricts the flow in the sewer pipe, resulting in a loss of hydraulic capacity. The presence of sediment in sewer flows has another minor effect on hydraulic performance of the sewer pipe. The presence of sediment in the flow or moving along invert cause a small increase in dissipation of energy and loss, and this observed as a reduction in discharge capacity of about 1% [1].

May[2] investigated the role of the sediments shape on the invert. He realized that above the threshold of the movement, sediment quickly forms into ripples and dunes and initially these grow in size and the flow velocity increases. Usually of greatest significance is the increase in overall resistance caused by the rough texture of the deposited bed. However, at higher velocities the dunes tend to reduce in size until the bed again becomes flat with much lower roughness. The loss of hydraulic capacity due to a deposited bed can therefore, vary considerably with the flow conditions.

1.2 Roughness of Deteriorated Wall

Corrosion of concrete in urban drainage system can be caused by the generation of hydrogen sulfide, H2S. In pipes flowing under gravity, H2S escaping into atmosphere from solution in the wastewater tends to rise and accumulate in condensation water on the soffit of the pipe. There, it is oxidized to form sulfuric acid which can cause serious damage to pipe material. This will remove the smooth lining and cover of the pipe and increase the roughness of the pipe which, leads to a higher degree of hydraulic loss.

Observations show that the most serious corrosions take place on the levels of frequently changing wastewater surface on the sides of the pipe cross section and on the soffit. Usually the designer considers a safety factor for the capacity of the pipe. Wastewater level by applying the peak factors should not increase to over 0.75d/D. The effect of roughness particularly at the end of design period is crucial.

1.3 Hazard of Increasing Roughness

Foul sewers should be designed to convey the predicted peak flows. It is conventional to restrict depth of flow (typically to d/D=0.75) to ensure proper ventilation.

Imagine a sewer is carrying the maximum flow rate just less than full. If there is an increase in flow entering the sewer, the carrying capacity of the pipe can no longer be increased by a simple increase in depth. In this case a new hydraulic gradient which is greater than the old one forms. If inflow continues to increase, the hydraulic gradient will increase. The obvious danger is that the hydraulic
gradient will rise above ground level. This may cause manhole covers to lift and the flow to flood onto the surface as a result of manhole surcharge.

In this work the effect of different local roughness on the capacity of pipes are examined. This may be changed from a point to another. First an equivalent roughness for a certain level of wastewater based on Darcy-Weisbatch formula is introduced. Then a comparison is made between the capacity of smooth and roughened pipe. Finally, as a second approach, the results obtained based on Darcy-Weisbatch formula are compared with those computed by Manning equation with an equivalent roughness.

2 A Model of Roughness

As reported, different type of deposits can be found in sewers. Two major parts are coarse granular material and fine grained deposits. Based on this classification the most significant type which may affect the hydraulic capacity of the sewers are coarse granular deposit. Under dry weather flow condition, sediment particles can form a highly concentrated layer which does not allow any flow through the material; and the only effect is surface roughness. Solids found in sewer pipes in Isfahan, a city in the central part of Iran with aired climate, were relatively large with a diameter over 0.8 mm.

The first step to model the roughness is to quantify it. Observations have shown that three major parts of different roughness can be considered in a sewer pipe. From bottom, the first part is located on the invert of the pipe with an angle of $\theta_1$. The magnitude of $\theta_1$ depends on the amount of sediments. It is assumed that sediments accumulated on the invert will not allow the flow to pass through. It is observed pipes with a large $\theta_1$ suffer a serious deterioration.

The second part of roughness is happening on the sides of the pipe with a magnitude of $\theta_2$ on each side. These parts of pipes are usually subjected to the fluctuations of flow due to non-uniform water consumption in a 24-hour period. Thus, the process of dry and wet frequency will intensify the rate of deterioration. It should be mentioned that in addition to this factor, the nature of wastewater significantly influences the corrosion.

In pipes flowing under gravity, H2S escaping into the atmosphere form solution in the wastewater tends to rise and accumulate in condensation water on the soffit of the pipe which may cause serious damage to pipe materials. Concrete is a material susceptible to H2SO4. The favorable condition of the production of hydrogen sulfide are: trade wastes with substantial sulfides or organic sulfur contents, low pH wastewater, high wastewater temperature, low wastewater velocity \[4\]. Also it is revealed that in gravity sewers under 600 mm in diameter the potential to emission of hydrogen sulfide is high \[2\].
To investigate the hydraulic performance of sewer pipes with different local roughness, a relatively large variation of corrosion, based on observations made in Isfahan sewer system, is considered (see Fig. 1(b) for a typical corrosion):

\[
\pi / 12 < \theta_1 = \theta_3 < \pi / 2 \ , \ \pi / 12 < \theta_1 = \theta_3 < \pi / 2 \ , \ \frac{\varepsilon_r}{\varepsilon_s} < 20
\]  

where the subscribes \( r \) and \( s \) refer to rough and smooth, respectively.

3 Governing equations

The pressure in pipe systems for sewerage is normally atmospheric, even if they carry the discharge to flow full. The Colebrook-White [3] equation may be used for finding the hydraulic performance of sewer pipes. It is assumed that the wastewater surface is parallel to the invert, so the hydraulic gradient equals the pipe gradient:

\[
S_0 = \frac{h_f}{L}
\]  

where \( S_0 \) is the pipe gradient.

A free surface flow has one more variable than full pipe flow, namely the height of the free surface. This can introduce considerable complexity. Let \( d \) be depth of flow in pipe with a diameter of \( D \), then other hydraulic parameters can be obtained as follows (see Fig. 1(a)).

(a) (b)

Figure 1: (a) Geometric properties of a sewer pipe and (b) A deteriorated pipe.

The cross sectional area of flow normal to the direction of flow (area):

\[
A = \frac{1}{8} (\phi - \sin \phi) D^2
\]  

The length of wetted surface measured normal to the direction of flow (wetted perimeter):

\[
P = \frac{1}{2} \phi D
\]
The width of channel surface at the free surface (surface width):
\[ T = \sin \left( \frac{\phi}{2} \right) D \]  (5)

The ratio of area to wetted perimeter (hydraulic radius):
\[ R_h = \frac{A}{P} \]  (6)

The ratio of area to surface width \((A/T)\) (hydraulic mean depth):
\[ D_h = \frac{1}{8} \left( \frac{\phi - \sin \phi}{\sin(\phi/2)} \right) D \]  (7)

For the case of circular conduits, the Colebrook-White equation may be modified to provide a solution. It can be assumed that the friction factor for the partially full conditions behave similarly to that for the full condition; it remains to find a parameter for partially full pipe which is equivalent to the diameter for the pipe case. The hydraulic radius, \(R_h\), is:
\[ R_h = A / P = \frac{\pi D^2}{4} / \frac{\pi D}{4} = \frac{D}{4} \]  (8)

Hence, the Colebrook-White transition law applied to partially full pipes becomes:
\[ \frac{1}{\sqrt{f}} = -2 \log \left( \frac{\varepsilon}{3.7 \times 4R_h} + \frac{2.51}{Re \sqrt{f}} \right) \]  (9)

where \( Re = 4R_h V / \nu \).

By the use of Darcy-Weisbatch equation and replacing \( h_f / L \) by \( S_0 \) gives:
\[ V^2 = 2gS_0 D / f \]  (10)

Hence for a given pipe with partially full flow we have:
\[ V = \sqrt{\frac{2gS_0}{4R_h \frac{4R_h}{f}}} \]  (11)
or
\[ V = \text{const.} \times \sqrt{\frac{R_h}{f}} \]  (12)

Forming the ratio \( V_d / V_D = V_p \) gives:
\[ \frac{V_d}{V_D} = V_p = f_D^{1/2} (R_h)_p f_d^{1/2} \]  (13)

where the subscripts \( p, D \) and \( d \) refer, respectively to the proportional value, the full depth and the partially full depth. Similarly,
Based on the definition given in Eqs. (3) and (4) we have:

\[ A_p = \left( \frac{\phi - \sin \phi}{2\pi} \right), \quad (R_h)_p = \left( \frac{1 - \sin \phi}{\phi} \right) \] (15)

Substitution of Eq. (15) into (16) allows calculation of the proportional velocity and discharge for any proportional depth \( d/D \). The expression for \( f \) (Eq. (9)) is however, rather cumbersome to manipulate. In the case of rough turbulent where \( f \) is only a function of relative roughness, we have:

\[ \sqrt{\frac{f_d}{f}} = 2 \log \left( \frac{3.7D}{\varepsilon} \right) \] (16)

Hence

\[ \sqrt{\frac{f_d}{f_d}} = \left( \frac{2 \log(3.7 \times 4R_h)}{2 \log(3.7D / \varepsilon)} \right) \] (17)

This may be expressed by its equivalent:

\[ \sqrt{\frac{f_d}{f_d}} = 1 + \frac{\log(R_h)_p}{\log(3.7D / \varepsilon)} \] (18)

Equation (18) may be substituted into (14) to yield:

\[ Q_p = \left( 1 + \frac{\log(R_h)_p}{\log(3.7D / \varepsilon)} \right) A_p (R_h)_p^{1/2} \] (19)

Now it is possible to draw the diagram of \( Q_p \) as a function of \( d/D \). The diagram can be found in any preliminary book (e.g. [5]), however, the described relationships can be used to obtain flow discharge in a non-uniform roughened pipe. All of the obtained results of a rough pipe are compared to the original smooth one. In all of the calculations it was assumed that the flow is fully turbulent and \( f \) is only a function of \( \varepsilon / D \).

4 Results

To investigate the effects of local roughness in hydraulic performance of the sewer pipes, two different approaches have been selected. The first one which considers the variation of relative roughness \( \varepsilon / \varepsilon_s \), deals with constant deteriorated perimeter \( (\theta = \text{const.}) \). Computations have been performed for four values of relative roughness, namely 5, 10, 15 and 20. Typical values of \( \theta_2 = \pi / 4 \) and \( \theta_1 = \theta_3 = \pi / 3 \) are used to obtain discharge characteristics of roughened pipe with \( \varepsilon / \varepsilon_s = 10 \) in compare to a smooth one.
In order to compute an equivalent roughness at a certain $d/D$, the production of roughness heights and the corresponded perimeters are summed up and the result is divided by the total perimeter.

The results of $(Q/Q_f)_r$ and $(Q/Q_f)_r$ are given in Fig. 2. It should be mentioned that $(Q/Q_f)_r$ implies the ratio of discharge capacity for a specified $d/D$ for rough pipe to the full capacity of a smooth pipe. As can be seen, the discharge capacity for larger $d/D$ in the case of rough pipe is distorted from the one of smooth pipe.

![Figure 2: Discharge characteristics of a roughened pipe.](image)

At $d/D=0.75$, as a design criteria, it can be seen that for a rough pipe as described, around 20% reduction in pipe capacity has occurred. For larger $d/D$, the amount of reduction will be increased up to 23%.

In Fig. 3 discharges for the cases of different roughness are depicted. From Fig. 3 (a) it is evident that as the roughness intensity increase, the rate of reduction of hydraulic capacity decreases, for example for the maximum rate of discharge which occurs at $d/D=0.94$, for $\varepsilon_r/\varepsilon_s = 5$, we have a reduction of 16%, meanwhile for $\varepsilon_r/\varepsilon_s = 10$, 15 and 20 at the same $d/D$ it reaches to 23%, 27% and 30%, respectively.

Fig. 3 (b) helps to get an idea of discharge reduction. In this figure it can be seen that due to deposition a great reduction of capacity up to $d/D=0.309$ occurs. However, for larger $d/D$ an increase of about 6% in discharge can be observed.

In Fig. 4 (a), for a moderate corrosion with a relative roughness of $\varepsilon_r/\varepsilon_s = 10$, for five different ranges of $\theta_1, \theta_2, \theta_3$, diagrams are depicted. This figure shows that the maximum difference between the discharges of rough and smooth pipes occurs at maximum discharge with $d/D=0.94$ and it reaches from 107% for a smooth pipe to 75% for a rough pipe.

Fig. 4 (a) also shows that as corrosion increases quantitatively, the discharge capacity decreases. In Fig. 4(b) another representation of Fig. 4(a) is given. This
diagram is extracted by dividing curve numbers 1 to 5 to curve number 0. As shown in Fig. 4(a) at $d/D=0.75$, $Q/Q_f$ is almost equal to 0.84. In this way in different roughness intensity which increases from case 0 for smooth to case 5 which roughened area occupies the whole pipe, a larger reduction of discharge capacity can be observed as roughness increases. In case 5, with the highest intensity of roughness, about 68% of discharge of a smooth pipe at $d/D=1.0$ can be delivered. In this case at $d/D=0.75$ only about 66% of discharge (in compare to a new pipe) can be passed and this means a reduction of 34% in discharge capacity.

![Figure 3: Discharge characteristics of different ratios of roughness](image)

(a) Relative discharge and (b) Relative reduction.

Now let's consider the discharge capacity of Fig.2. The reduced discharge capacity at a certain $d/D$ is due to two different sources of roughness, sediments and corrosion pipe wall.

To realize the effect of each source individually, we have depicted the discharge capacity for a deposited pipe with $\theta_2 = \pi/4$ and $\theta_1 = \theta_3 = \pi/3$ in Fig.5(a). In Fig.5(b) the ratio of reduced discharge due to deposited material to the discharge of a smooth pipe is plotted. Almost 82% of $Q$ for smooth pipe with sediment will be passed at $d/D=0.75$.

In Fig.5(b) the effect of wall roughness on the discharge capacity is depicted associated with discharge capacity for a smooth pipe. In this figure the ratio of these two curves is plotted. As seen, the maximum discharge reduction occurs at $d/D=0.75$ with an amount of 84% in compare to smooth pipe.
Figure 4: Discharge capacity for different magnitude of corrosion
(a) Discharge and (b) Reduction percent.

Figure 5: Discharge characteristics of a
(a) Deposited pipe and (b) Roughened pipe.

From a comparison of Figs. 5(a) and 5(b), it is observed that for larger values of $d/D$ almost about 17$\%$ of discharge capacity is reduced which is nearly equal for two cases. Meanwhile, for the case of deposited pipe, for smaller values of $d/D$, reduction from the full flow is increased.
In Fig. 6(a), Manning formula is used for the estimation of discharge capacity for a variation of relative roughness $1 < \varepsilon_r / \varepsilon_s < 20$. The equivalent Manning coefficient can be obtained by the use of Horton[6] formula as equivalent roughness.

This figure shows when relative roughness is $\varepsilon_s$ (with a constant magnitude of corrosion $\theta_1 = \theta_3 = \pi / 6$ and $\theta_2 = \pi / 4$), at $0 < d/D < 0.067$, $Q_r / Q_s = 0$ and in the range of $0.067 < d/D < 0.309$ under the effect of deposition, $Q_r / Q_s << 1$.

In the range of $0.309 < d/D < 0.691$ a little change in the pipe capacity can be observed with a relative larger reduction for smoother pipes. It should be mentioned that in this range the roughness of side wall is responsible for that. In the range of $0.691 < d/D < 0.933$, the maximum relative discharge occurs at $d/D = 0.933$ with a reduction of relative discharge varying from 87% to 78% for $5 < \varepsilon_r / \varepsilon_s < 20$.

A comparison of Fig. 6(a) and 2 shows that using Manning equation leads to less relative reduction in discharge. At $d/D = 0.75$ which is significant for the selection of the sewer pipes, for $\varepsilon_r / \varepsilon_s = 5, 10, 15$ and $20$, we have $Q_r / Q_s = 0.84, 0.80, 0.77$ and 0.74, respectively.

In Fig. 6(b), for the range of $1 < \varepsilon_r / \varepsilon_s < 20$, variation of $n_r / n_s$ is plotted. This diagram is obtained for equal depth of flow. It can be seen for $0.067 < d/D < 0.309$, a great variation in $n$ occurs. For example, for $\varepsilon_r / \varepsilon_s = 5$, $n_r / n_s$ varies between 1 and 1.25 and the variation for $d/D > 0.309$ is relatively small and restricted between 1.1 and 1.14. This variation can also be observed for other relative roughness, however, as $\varepsilon_r / \varepsilon_s$ increases $n_r / n_s$ takes larger values. For $\varepsilon_r / \varepsilon_s = 20$ at $d/D = 0.7$, $n_r / n_s \approx 1.31$ with a mean range of 1.26.
Concrete pipes will be damaged during their life. This damage not only affects the structural behavior of pipes but also the hydraulic ones. On the other hand sedimentation may occur on the invert of the pipe. These two effects will lead to a smaller discharge capacity. Generally, the worst circumstance of hydraulic performance of a sewer pipe will be occurred at the end of design period. So, this situation should be considered in design procedure. It is obvious that the discharge capacity of a pipe depends on the intensity of corrosion and deposition qualitatively, as well as quantitatively. Calculations have shown that for a typical and moderate roughness, about 25% of discharge reduction occurs at $d/D=0.75$. In the most critical situations it will reach to 34% reduction in pipe capacity. This shows a very critical situation. If due to some overloads in the sewer system, the depth of flow in pipe increases, surcharge may happen and the hazard of flowing wastewater on the ground will be inevitable. Thus, it is recommended that the worst situation during the period of design for the design of sewer pipes be selected.

References


