Pressure-Flow and Free-Flow Discharge Modes in Closed-Loop Sewage Systems

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Abstract. The paper discusses flow modeling in closed-loop sewage systems. These systems take place in reconstruction and development of sewage systems. The waste flow values which are distributed over individual closed-loop sewers are proposed to be determined on the basis of the solution of the conservation equation for mass and energy. This article presents these equations for the cases of pressure-flow and free-flow of drains and calculating examples of all these cases. The issues of improving the reliability of sewage systems by transferring them to a closed-loop structure are considered.

1. Introduction.
A common approach in the design of gravity-flow sewage systems is to assume a treelike structure for the network, with users as the leaves and receiving tanks of wastewater treatment facilities at the root. Such a layout offers operational efficiency together with cost savings and allows to dispense with additional flow control systems. However, systems designed this way suffer from reliability and safety problems. Any congestion within a trunk pipeline would result in wastewater overflowing to the surface, resulting in significant environmental damage. Further complicating the problem in many cases is the difficulty of transferring wastewater into another sewer or pit located downstream. As a result, wastewater would continue to rise to the surface until the obstruction is cleared and operation of the constricted pipeline resumes. Development of urban territories faces the issue of upgrading storage capacity and throughput of sewers, making it necessary to lay new pipelines, set up pumping stations and carry out other measures necessary for ensuring normal operation of the entire sewage system. A common solution to that end includes closed-loop unloading sewers. Figure 1 provides a summary of designs of such sewer systems.

Individual closed-loop pipelines may operate both in free-flow and pressure-flow modes. Possible designs include installation of wastewater pumping stations, laying of parallel pressure pipelines with cascades of pumping stations, etc.

The existing practice for flow control in closed-loop sewer systems is based on the use of gate valves for widening or narrowing the flow section of any particular sewer. As a rule, gate valves operate in manual or semiautomatic mode, however modern designs make remote control possible. In order to ensure efficient operation of such devices, it is necessary to survey hydraulic features of flow distribution in closed-loop free-flow and semi-free flow sewage systems.
2. Methods.
It is well known that the distribution of flows in a closed-loop pressure network behaves in accordance with mass and energy conservation laws and can be interpreted in terms similar to Kirchhoff’s circuit laws. Problems of flow distribution in pressure pipeline networks have been studied by researchers, and multiple software programs are available enabling flow rates to be determined online, both system-wide and on the level of individual sections and components [1-8] .

Obviously, the distribution of flows for semi-free flow closed-loop manifolds would similarly follow the laws of conservation of mass and energy.

Figure 2 shows a pit which receives a wastewater flow of \( Q \) through a single sewer and distributes it across three sewers installed at various levels.

At the first step of computation, flow rates in sewers are determined as if the entire available sewer cross-section area was utilized i.e. \( Q_{a1}, Q_{a2}, Q_{a3} \).

Obviously, at \( Q_{a1} > Q \) the first and second sewers will handle the entire flow rate in the free-flow mode; the same holds for \( Q_{a2} + Q_{a3} > Q \). If \( Q_{a1} + Q_{a2} + Q_{a3} < Q \), then all sewers will operate in the pressure-flow mode.

In order to compute wastewater flow rates, the pit is divided into the following zones along its full height:

The first zone extends from \( Z_{H1} \) to \( Z_{H2} \). Within this zone, flows will be transported in free-flow mode in the first sewer only.

\[
Q_1^{(k)} = \left( \frac{1.34 \cdot P^{(k-1)} - Z_{H1}}{d_1} - 0.22 \right) \cdot Q_{a1},
\]

\[
P = Z_{H1}, \ldots, Z_{H2}; \left| Q_1^{(k)} - Q \right| \leq \varepsilon
\]
If no solution is found, the second zone should be considered, spanning $Z_{H2} - (Z_{H1} + d_1)$

Two sewers will operate in free-flow mode within this zone:

$$Q_1^{(k)} = \left(\frac{1.34 \cdot P^{(k-1)} - Z_{H1}}{d_1} - 0.22\right) \cdot Q_{o1}, \quad Q_2^{(k)} = \left(\frac{1.34 \cdot P^{(k-1)} - Z_{H2}}{d_2} - 0.22\right) \cdot Q_{o2},$$

$$P = Z_{H2} - (Z_{H1} + d_1); |Q_1^{(k)} + Q_2^{(k)} - Q| \leq \epsilon$$

If no solution is found, the third zone should be considered: $Z_{H1} + d_1, ..., Z_{H2} + d_2$.

Within this zone, the first sewer will turn into pressure-flow mode while the second one will continue in the free-flow mode.

$$Q_1^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k1}^{(k-1)}}{\beta_1}}; \beta_1 = \frac{0.215}{d_1^2} + \frac{0.08 \cdot \lambda \cdot t}{d_1^3}$$

$$Q_2^{(k)} = \left(\frac{1.34 \cdot (P^{(k-1)} - Z_{H2}) - 0.22}{d_2}\right) \cdot Q_{o2},$$

$$P = Z_{H1} + d_1, ..., Z_{H2} + d_2; |Q_1^{(k)} + Q_2^{(k)} - Q| \leq \epsilon$$

If still no solution is found, the next zone should be considered: $Z_{H2} + d_2, ..., Z_{H3}$.

Both the first and the second sewers will operate in pressure-flow mode within this zone.

$$Q_1^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k1}^{(k-1)}}{\beta_1}}; \quad Q_2^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k2}^{(k-1)}}{\beta_2}};$$

$$P = Z_{H2} + d_2, ..., Z_{H3}; |Q_1^{(k)} + Q_2^{(k)} - Q| \leq \epsilon$$

If still no solution is found, the next zone should be considered: $Z_{H3}, ..., Z_{H3} + d_3$.

All three sewers will operate within this zone, the first and second sewers operating in the pressure-flow mode and the third sewer operating in the free-flow mode:

$$Q_1^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k1}^{(k-1)}}{\beta_1}}; \quad Q_2^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k2}^{(k-1)}}{\beta_2}}; \quad Q_3^{(k)} = \left(\frac{1.34 \cdot (P^{(k-1)} - Z_{H3}) - 0.22}{d_3}\right) \cdot Q_{o3},$$

$$P = Z_{H2}, ..., Z_{H3} + d_3; |Q_1^{(k)} + Q_2^{(k)} + Q_3^{(k)} - Q| \leq \epsilon$$

If still no solution is found, the next zone should be considered: $Z_{H3} + d_3, ..., Z_3$.

All three sewers will operate in pressure-flow mode within this zone:

$$Q_1^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k1}^{(k-1)}}{\beta_1}}; \quad Q_2^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k2}^{(k-1)}}{\beta_2}}; \quad Q_3^{(k)} = \sqrt{\frac{P^{(k-1)} - P_{k3}^{(k-1)}}{\beta_3}};$$

$$P = Z_{H3} + d_3, ..., Z_3; |Q_1^{(k)} + Q_2^{(k)} + Q_3^{(k)} - Q| \leq \epsilon$$

If no solution is found so far, this means that wastewater will overflow to the surface. The respective flow rate can be computed using (4):
\[ Q_1 = \sqrt{\frac{Z_3 - P_{i1}}{\beta_1}}; Q_2 = \sqrt{\frac{Z_3 - P_{i2}}{\beta_2}}; Q_3 = \sqrt{\frac{Z_3 - P_{i3}}{\beta_3}}; \]

\[ Q_{3,i} = Q - (Q_1 + Q_2 + Q_3) \]

where \( Q_{3,i} \) is the flow rate of wastewater overflowing to the surface.

Thus, the proposed hydraulics formulas make it possible to determine wastewater flow rates in closed-loop sewers operating in pressure-flow, semi-free flow and free-flow modes [9,10].

As mentioned above, reliability and safety of sewage systems may be improved by means of designs which minimize clogging and other disruptions. Another option involves setting up closed-loop sewers or entire closed-loop sewage networks. Such measures would help to avoid shut-offs of operating sewers. On the other hand, they will improve throughput and agility of the sewage system as a whole. At the same time, experience with design and construction of closed-loop sewage systems is still far from sufficient, as hydraulic, techno-economic and operational features of free-flow closed-loop pipeline systems have not been studied well enough.

In the case of a pressure-flow wastewater flow, similar to closed-loop water pipeline systems, flows are distributed in accordance with mass and energy conservation laws. A specific feature of sewage systems is the possibility of wastewater overflowing to the surface in the pressure-flow mode. To simulate such events, it is proposed to solve the flow distribution problem using an expanded circular diagram whereby each pit is modeled with a putative branch connected to a node with atmospheric pressure and effective heads equal to geodetic elevations of pits [11-14]. In this case the combined equations analogous to the first and second Kirchhoff’s circuit laws will appear as:

\[ A \cdot q = 0 \]

\[ A^T P = y; \quad y_j = h_i + Z_i \]

Equations are presented here in vector-matrix form. Equations (1) specify the condition of material balance within the nodes of the diagram; the vector \( q \) represents flow rates along the branches of the diagram. Equation (2) represents the relationship between piezometric flow rates in nodes \( P \) across differentials \( y \) within network areas corresponding to summary head losses \( h \) and effective heads \( Z \) – elevations of ground surface around the pits) for putative branches. \( A \) is the connection matrix for nodes and branches of the diagram. Its dimensions are as follows: \( A = [a_{ij}]_{m \times n} \); \( m, n \) are the numbers of nodes and areas on the diagram, \( j = 1, \ldots, m; \quad i = 1, \ldots, n \). Here \( a_{ij} = -1 \) if the branch \( i \) is directed toward node \( j \); \( a_{ij} = 1 \) if the branch \( i \) exits from the node \( j \); \( a_{ij} = 0 \) if the node \( j \) does not belong to the area \( i \).

Similar to the method described in paper [15,16], an approach for consecutive and iterative solution of combined equations (1), (2) is proposed for closed-loop sewers based on the cyclical diagram with subsequent analysis of flow rates in putative branches. In this case, if the putative branch is routed to a sewer node, then wastewater discharge for this node shall be fixed at \( Q \) and the putative branch shall be removed from the diagram. Ultimately the remaining branches will have flows directed from pits to the atmospheric-pressure node, with flow rates in these branches corresponding to the surface overflow rates. If no putative branches remain in the solution diagram after such computations, then surface overflowing will not occur. Figure 3 illustrates the original cyclic diagram of wastewater pressure flows in closed-loop sewage systems together with the results of computation. As it follows from the results, pits 1, 5 will have surface overflows and pits closest to them will experience counterflows.
Figure 3. Simulation of flow distribution in pressure-flow closed-loop sewage systems

It should be noted that closed-loop sewage systems which operate in pressure-flow mode may have branch flows directed upstream against pipeline slope. It is important to consider this possibility with regard to the design and operation of such systems [7,8]. It is impossible to know beforehand whether wastewater flows will run in pressure-flow or in free-flow mode. In either case computations begin with solving problem (1), (2) using an expanded circular diagram. If neither surface overflows nor counterflows are found to occur, flow rates in individual areas of the network shall be compared to the full cross-section wastewater flow rates. If, for all areas, $q_i > q_{in}$, then a pressure flow will develop, and the computation shall be deemed complete. If, for all areas, $q_i < q_{in}$, this means that a free flow mode will develop. For the free-flow mode, the closed-loop network can be viewed as an oriented graph with sewer slope determining flow direction [17-20].

3. Conclusions.

The foregoing summarizes a computational method for the design of closed-loop sewage systems and its implementation in the TRACE-K software suite. Designers using the method and the software suite will benefit from supported design parameters of closed-loop and unloading collectors for sewage system redesign and development projects. Operator companies may find the TRACE-K software suite useful as a part of supervision control for troubleshooting and optimization of wastewater transportation modes. In the case of automated flow distribution the present method can be used to pre-compute control actions for gate valves and to simulate the effects of their opening or closing [9-14].

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