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PHYSICAL MODELING TO DETERMINE HEAD LOSS AT SELECTED SURCHARGED SEWER MANHOLES

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Abstract

The head losses at sewer pipe junctions (manholes) under surcharged conditions were measured in a 1:6 scale model of a typical manhole with one main line passing through it and two perpendicular lateral lines flowing into it. Head-loss coefficients were determined for a variety of outlet-flow Reynolds number, surcharge level, pipe configurations and size, and inlet-flow contribution. Empirical formulas were also developed to estimate head-loss coefficients. The results indicate that head loss is insensitive to the amount of surcharge, but heavily depends on the flow configuration, relative flow rate, and pipe size ratio. The head loss becomes significant in the manhole junctions when there exists lateral inflows or the junction forces a change in direction. For many inlet flow conditions, the manhole loss is equivalent to 200-400 extra feet of pipe.

Introduction

Municipal sewerage systems are normally designed to operate without surcharging. That is, in each line, the water level is below the crown elevation. Flow in the pipe network is then gravity-driven, and is modeled as open-channel flow. However, if the inflow exceeds the pipe-full capacity of the pipeline, or if it is affected by a backwater from a downstream flow constraint, the system will surcharge (pressurized flow). The head loss through a gravity flow junction is often neglected during normal flow. However, when the system is surcharged manhole junction losses may become important and will comprise a significant percentage of the overall losses within a sewer system, especially in large systems with many junctions. It is essential to incorporate the effect of manhole head loss into the design of sewer pipe lines so that the system can store excess flow, without flooding and overflows.

The physical modeling to determine junction head loss has been conducted by Acker (1959), Hare (1983), and Marsalek (1985). A submerged jet theory for estimating head-loss in straight through manholes was presented by Pedersen and Mark (1990). Most of these studies were either limited to equal pipe sizes or focused only for a few simple manhole configurations. Losses at sewer junctions are dependent upon

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flow characteristics, junction geometry, and relative sewer diameters. In this study, we conducted a series of comprehensive laboratory tests to determine the head-loss coefficients through manhole under a variety of piping configurations and flow rates. These head-loss coefficients can be used in predictive hydraulic models for design and operation of the sanitary collection system as part of the rehabilitation project of the sewer systems in Houston area.

Manhole Head Loss and Head-Loss Coefficients

Under surcharged conditions, flow in each of the lines connected to a manhole is pressure-driven. At any point on these lines, the total head H consists of piezometric head and velocity head. To describe the energy losses at a manhole junction, we apply mass and energy balances to the control volume consisting of the manhole itself, with three inlet sections and one outlet section. The manhole head loss ΔH_i (i =m, a, or b; where m, a, and b refer to the main line, lateral A, and lateral B, respectively) for any inlet line is written as

$$\Delta H_i = \left(h_i + \frac{V_i^2}{2g} \right) - \left(h_o + \frac{V_o^2}{2g} \right) \quad , \qquad (1)$$

where h = piezometric head; V= velocity; g= acceleration due to gravity; and subscripts i and o represent the inlet line and outlet line, respectively. It is customary to then define the dimensionless head-loss coefficient, K_i as

$$K_i = \Delta H_i \, / \, \frac{V_o^2}{2g} \quad . \qquad (2)$$

Model Construction and Test Procedure

The physical model of the sewer pipe and manhole system was constructed at an undistorted scale of 1: 6 in the Hydraulics Laboratory of the University of Houston. The model layout is illustrated in Figure 1. The physical modeling system is about 40 ft long in the main line axis and 20-ft long in each lateral line. The junction model is a typical manhole with a main inlet, designated "M", and two lateral lines, designated "A" and "B", flowing into the model and a single outlet, designated "O" leaving model. The pipes are supported by eight steel-frame tables which could be adjusted to any given slope by means of screw jacks. A 1/1000 pipe slope was used for the test. A 5 hp pump was used to supply water from storage tanks to three head tanks to provide head needed for the flow through the system.

The basic manhole model is an 8-inch diameter and 40-inch high circular manhole base with four openings for 4-inch PVC pipe around its circumference at the base. The manholes were designed to represent typical configurations used in current sewerage practice. Semi-circular flow channels are cut into the base to model the typical "benching" of manhole design.

Each line is instrumented with 6 manometers. Readings from these manometers established a hydraulic grade line in each inlet line and outlet line. An ultrasonic doppler-shift flowmeter was attached to each line to measure the velocity in the line, from which the velocity head was calculated. Total discharge is measured at the outlet using a calibrated sharp-crested weir. By blocking one or more of the inlets with plugs, or switching the manhole base model a variety of flow configurations with different pipe diameters (2 inch, 3 inch, and 4 inch) were investigated.

The model was first set up with desired inlet pipe sizes and manometers for each inlet line were connected via 1/4-inch tubes tapped directly into the wall of the line. The ultrasonic flowmeter for each line was calibrated by comparison to the weir discharge measurement. System control valves were set and the water was pumped to the head tanks then flowed to the manhole piping system. By adjusting the inlet flow rates and the downstream valve, a surcharged flow condition was introduced in the manhole junction. The flow was recirculated until it reached the steady state. The weir head, velocities of inlet lines, and the manometer heights were measured.

Tests were conducted for various flow rates, pipe sizes and for flow configurations of straight, T junction, cross, 90° bend and 45° bend. Manhole configuration is indicated by the notation $d_m d_a d_b d_o$ with all diameters in inches; for example, 4334 indicates that the main line diameter is 4 inches, lateral A and B are both 3 inches, and the outlet line diameter is 4 inches. An X in the configuration name indicates that the corresponding line is plugged, for example, X334 indicates a T-junction with 3 inch laterals and a 4 inch outlet line.

Determination of Head-Loss Coefficients and Equivalent Pipe Length

A procedure to determine head-loss coefficients for the main inlet line and laterals at manhole junctions is presented in Figure 2. The best-fit straight lines shown in Figure 2 display the total energy grade lines for main inlet line, lateral A, lateral B and outlet line, respectively. The total head is computed for each manometer and plotted against manometer distance from the center of the model. The best-fit straight lines are extended through the model center. The difference in intercepts between each inlet line and outlet line represents the associated head loss due to the presence of manhole junction. The head-loss coefficient is then determined from equation (2).

The manhole head loss can also be conceptually transferred to as the equivalent friction loss due to the existence of conceptually added pipe length. This additional pipe length is defined as the equivalent pipe length. The equivalent pipe length can be conceptually added into the actual designed pipe length for pipeline modeling to reflect the effect of manhole head loss. However, physically the actual pipe length remains unchanged. The equivalent pipe length (in British system) for the manhole head loss along the inlet lines (i = m, a,b) can be determined using Darcy-Weisbach equation and Manning's equation as

$$L_i = \frac{D_i^{4/3}}{5.75\ g\ n^2} \frac{V_o^{\ 2}}{V_i^{\ 2}}\ K_i \qquad (3)$$

where n is the Manning's roughness coefficient and D_i is the pipe diameter of inlet line.

Results

The manhole head losses were measured for all flow configurations and mixed pipe sizes. For each test case, the data were analyzed and the head-loss coefficients were calculated. The dependence of head-loss coefficients on outflow Reynolds number and surcharge level are first examined. Figures 3 and 4 present typical set of results reflecting the tests of outflow Reynolds number (Re) dependence for 4334 and 4444 manhole configurations. From Figures 3-4 and other related measurements, we note that head-loss coefficients are in general independence of Reynolds number in the range typically seen in surcharged sewer flow. The dependence of head-loss coefficients on surcharge level was also studied. The measured data show that the head-loss coefficients are independent of surcharge level.

The results for the cases of 4-inch main line and laterals are presented to show the typical variations of head-loss coefficients under different flow rates and manhole configurations. From measured data, two empirical formulas to determine the head-loss coefficients K_m and K_a for the 4-inch lines were given as

$$K_m = 0.742 + 0.65\, q_m + (q_a - q_b)^2\,[\,0.003 + 1.307\, q_m\,] - 2.38\, q_m^{\,2} + 1.08\, q_m^{\,3} \qquad (4)$$

$$\begin{aligned} K_a = {} & 0.966 - 0.016\,(q_a - q_b) - 0.427\, q_m + 0.56\,(q_a - q_b)^2 \\ & + 0.948\, q_m\,(q_a - q_b) - 1.073\, q_m^{\,2} - 0.116\,(q_a - q_b)^3 \\ & + 0.373\,(q_a - q_b)^2\, q_m - 0.886\,(q_a - q_b)\, q_m^{\,2} - 0.252\, q_m^{\,3} \end{aligned} \qquad (5)$$

where q_m, q_a, and q_b are flow fractions ($q_m = Q_m/Q_o$, $q_a = Q_a/Q_o$, $q_b = Q_b/Q_o$). For K_b, use the K_a formula with q_a and q_b interchanged.

Triangular contour plots of the head-loss coefficients K_m and K_a using these formulas are shown in Figures 5 and 6 respectively. In each plot, each of the q_i (i = m, a, or b) is scaled linearly from the side of the triangle labeled " $q_i = 0$" to the opposite vertex, labeled "q_i = 100%". At any point in the triangle, $q_m + q_a + q_b$ = 100%. Contour lines show the corresponding K_m and K_a values. It is found the head-loss coefficients heavily depend on the relative flow rates and flow configurations. The results indicate the head loss is less significant for a straight flow configuration. However, the head loss becomes significant in the manhole junctions when there exists lateral inflows or the junction forces a change in direction. For the design purpose, this manhole head loss might need inclusion in the pipeline simulation. Based on our results, scaled for 24-inch prototype pipelines, a general rule of thumb of adding 200 to 300 ft of equivalent pipe length to the main line or laterals in the hydraulic modeling is suggested to reflect the effect of the manhole head loss.

In this study, we have conducted a comprehensive model tests for measuring manhole head losses. The measurements consider various flow configurations, flow rates, and relative pipe size (e.g. the configurations of 4444, 4334, 4224, 3224, and 3334). A complete summary of the head loss coefficients, equivalent pipe lengths and empirical formulas for all test cases can be found in Wang et al. (1995).

The variations of K_m and K_a versus flow rate of q_a for the 44X4 (T junction) configuration (open squares) are plotted in Figures 7 and 8, respectively. For comparison, both figures also show the results of Marsalek (1985, Mould M2) from the similar configuration (plotted as filled triangles). The agreement are generally very good. The flow pattern of 4444 with $q_b = 0$ is generally similar to the 44X4 flow configuration. The head-loss coefficients for 4444 with $q_b = 0$ are presented with filled squares. It is interesting to note, within the estimated errors, coefficients for both configurations are nearly the same.

Conclusions

The head losses at sewer pipe junctions under surcharged conditions may be comparable to friction losses and require their inclusion in the hydraulic pipeline modeling to adequately predict system performance. In this study, we built a physical model to measure the manhole head losses. Empirical formulas to estimate head-loss coefficients were also developed. The general conclusions are summarized in the following:

1. The head-loss coefficients are strongly dependent on relative pipe diameters and flow proportions.

2. The head loss is less significant for a straight flow configuration. However, the head loss becomes significant in the manhole junctions when there exists lateral inflows or the junction forces a change in direction. In some cases, those head-loss coefficients can be over 25 times larger than the straight-through case.

3.The manhole head loss increases as the inlet pipe size decreases (or as the relative expansion increases). Also, as the lateral flows become more unequal the lateral loss coefficients increase dramatically.

4. In many cases, the manhole head loss is equivalent to the loss produced by several hundred feet of pipe.

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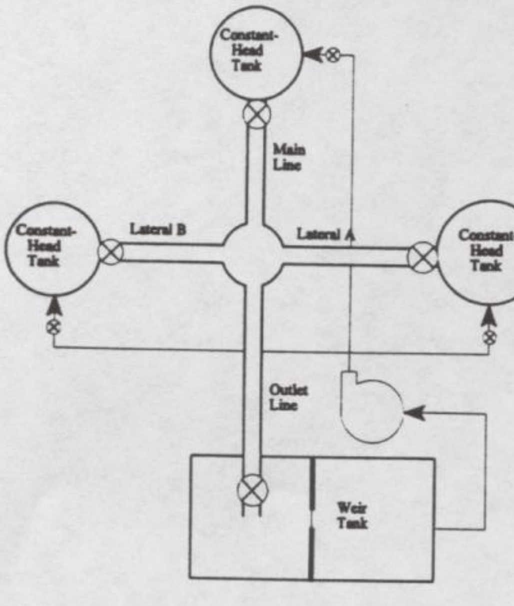

Figure 1. Schematic layout for head loss measurements in a manhole junction system.

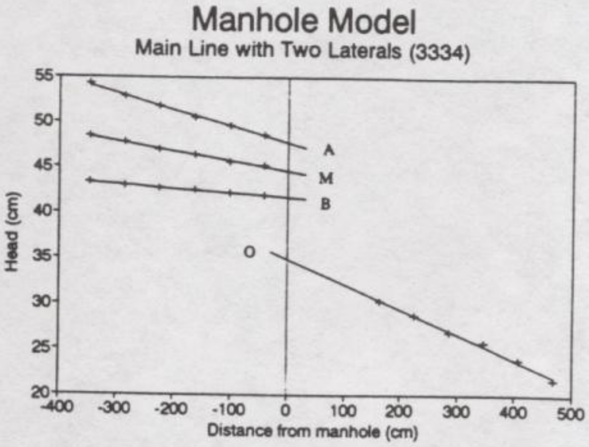

Figure 2. A typical energy grade line plot to show the head losses between inlet lines and outlet line.

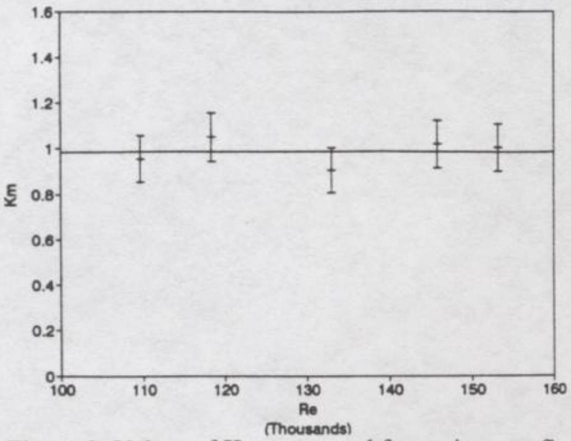

Figure 3. Values of K_m measured for various outflow Reynolds Numbers. ($q_m \approx 35\%$, $q_a \approx 35\%$, $q_b \approx 30\%$ in 4334 configuration.)

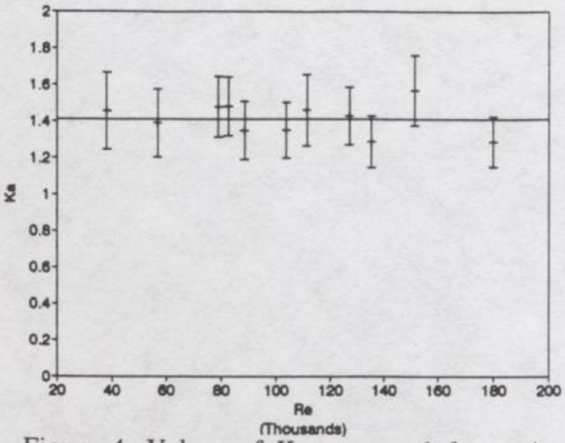

Figure 4. Values of K_a measured for various outflow Reynolds Numbers. (q_a=100% in 4444 configuration.)

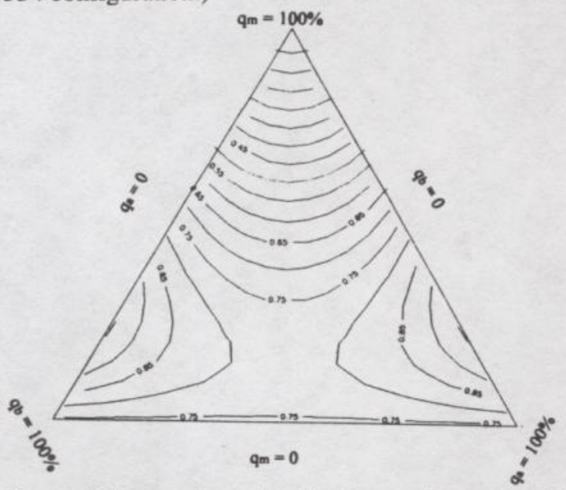

Figure 5. K_m contour plot for the configuration of 4444 and others.

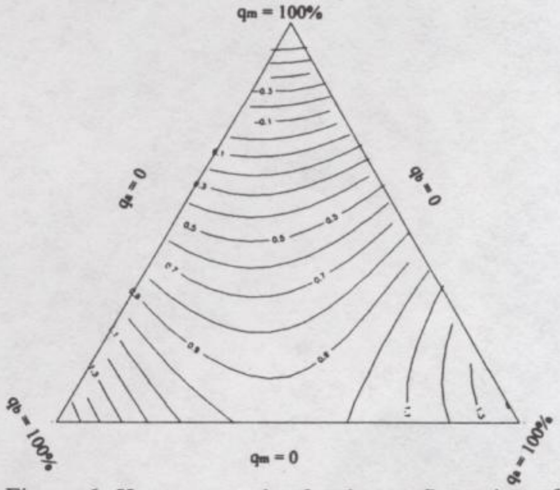

Figure 6. K_a contour plot for the configuration of 4444 and others.

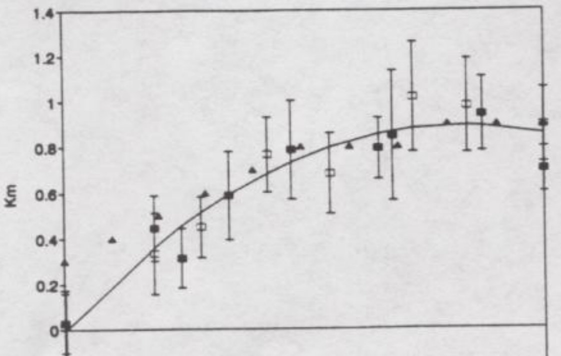

Figure 7. Variation of K_m versus flow rate of q_a for the 44X4 (T) junction; Open squares: 44X4, Filled squares: 4444 with $q_b = 0$, Filled triangles: Marsalek (1985, M2), and Solid line: Best quadratic fit to current data.

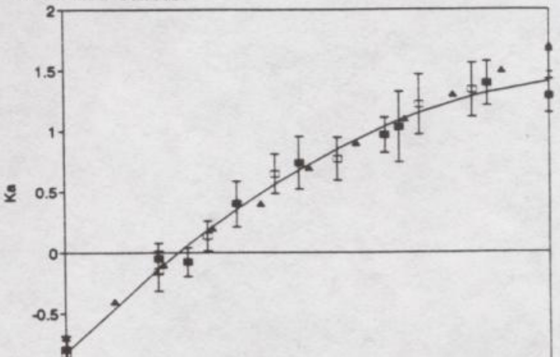

Figure 8. Variation of K_a versus flow rate of q_a for the 44X4 (T) junction; Open squares: 44X4, Filled squares: 4444 with $q_b = 0$, Filled triangles: Marsalek (1985, M2), and Solid line: Best quadratic fit to current data.