Groundwater Migration in Sewer Trenches

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When sources of infiltration and inflow are identified in a sanitary sewer system, the selection and priority of sources for rehabilitation can be established with a cost-effectiveness analysis. A source is cost effective to remove if its rehabilitation cost is less than the transportation and treatment cost for the source to remain in the system.

In a typical infiltration and inflow reduction program, the total infiltration in a basin is quantified with flow monitoring at a specific point, such as a manhole, pump station, or treatment plant, and with a comparison to water consumption records. If it is deemed that the infiltration in the basin is unacceptably high, a field investigation is conducted to locate specific defects that contribute groundwater infiltration into the sanitary sewer system. The investigation consists of inspection of manholes and of internal television inspection.

When defects are identified, they are also quantified in terms of an infiltration rate. Individual sources are quantified in one of three ways:

- Direct measurement if active, such as a leak through a manhole wall;
- Theoretical estimate, such as computing the flow rate through a manhole through a precast section lift hole of known dimensions;
- An empirical default rate based on the type of defect, such as assigning 0.1 gpm to all joints with light roots.

The defect quantification process relies greatly on experience; nevertheless, when properly done, the summation of all identified defects will equal the flow monitored infiltration if the field investigation is performed comprehensively.

The next step is to design the rehabilitation of sources of excessive flow and to predict the overall reduction of infiltration that will be achieved. The temptation is to assume that rehabilitation will remove 100 percent of the quantified infiltration. The reality is that the infiltration reduction achieved falls short. Post-rehabilitation television inspection reveals that though the rehabilitated sources are dry, other defects have become active or have become more active. We will attempt to explain the mechanism by which groundwater migration occurs in sanitary sewer systems.

Basic Principles

One dimensional groundwater velocity through a homogeneous soil follows the following equation, based on Darcy's Law:

$$v = ki \qquad (1)$$

where
v = flow velocity
k = permeability coefficient of the soil
i = hydraulic gradient

The permeability of the trench as a whole is greater than the permeability of the surrounding soil for the following reasons:

- The trench material is comprised of granular materials, more porous than surrounding soil.
- Even if native material is used, it can never be compacted to the same level as the surrounding soil. As a consequence, groundwater generally moves faster in the trench, especially if there is relief when groundwater reaches the lowest point of the sewer system, such as at a pump station or a treatment plant.

The composite coefficient of horizontal permeability in a sewer trench where different soil types exist in layer is governed by the following equation:

$$k_c = \sum_{j=1}^{n} \frac{k_j h_j}{h} \qquad (2)$$

where
j = soil layer designation
h_j = height of groundwater for layer j
k_j = permeability for layer j
k_c = composite permeability
h = height of groundwater over defect

Infiltration into a sewer defect can best be described by the orifice equation:

$$Q_1 = CA\sqrt{2gh} \qquad (3)$$

where
Q_I = infiltration flow rate into the sewer
C = orifice coefficient, depends on shape of the orifice
A = cross-sectional area of defect
g = gravitational constant

Groundwater Movement in the Trench

The flow of groundwater from surrounding native material perpendicular to the trench can be expressed as follows:

$$Q_T = v\,d\,L \qquad (4)$$

where
Q_T = flow to the trench per unit lineal length of trench
v is computed from equation 1
d = depth of groundwater above sewer trench
L = lineal length of trench

For this analysis, groundwater is assumed to be flowing in one direction: essentially perpendicular to the trench.

As groundwater moves over a defect, some of it enters the sewer, based on Equation (3). The rest continues downstream. The groundwater flow that continues beyond a defect at location 2 is

$$Q_l = Q_1 + Q_T\Big]_1^2 - Q_1 \qquad (4)$$

where
Q = total groundwater flow in trench
1,2 = defect designation where defect 2 is downstream of 1
Q_l = groundwater flow in trench past defect 1

Note that the groundwater trench is totally drained when

$$Q_l = Q_1 + Q_T + Q_H \qquad (6)$$

where
Q_H = groundwater flow below the defect. The composite permeability coefficient for Q_H is based on the soil layers below the defect whose total height is d-h.

Example

Given: For the trench depicted in Figure 1 with a standard coefficient of permeability of

$1k_s$ = 0.134 ft/day and,

w	=	3.0	h_c	=	0.5	x	=	100
d	=	3.0	h_b	=	1.0			
d_p	=	0.67	h	=	1.33			

Assume:
$k_1 = 10^2 = 13.4$ ft/day = 0.000155 ft/s
$k_2 = 10^5 = 0.155$ ft/s
$k_3 = 10^4 = 0.0155$ ft/s

First, find velocities through trench and surrounding soil. Determine composite permeability of trench, using equation (2):

$$k_c = \frac{[0.0155\ (h-h_c)] + [0.155\ (h_c + d_p + h_b)]}{d}$$

$$= \frac{[0.0155\ (1.33 - 0.5)] + [0.155\ (0.5 + 0.67 + 1.0)]}{3}$$

$$= \frac{0.0129 + 0.3364}{3} = 0.1164 \text{ ft/s}$$

Compute velocity in trench (V_c) from Equation (1).

$$V_c = k_c\ (i)$$

$$= 0.1164\ (0.004) = 0.000466 \text{ ft/s}$$

where hydraulic gradient (i) is equal to pipe slope (0.004).

Next, find Q_l, flow in trench

$$Q_l = V_c A = V_c\ (w)\ (d)$$

$$= 0.000466\ (3.0)(3.0)$$

$$= 0.0042 \text{ ft}^3\text{/s} = 1.89 \text{ gpm} \quad (\text{note: } 1 \text{ ft}^3\text{/s} = 448.83 \text{ gpm})$$

The height of groundwater at the downstream defect can be simulated by treating the upstream defect as an ordinary, perfect well. With this assumption, use of the Depuit equation provides a formula for the general shape of the depression line resulting from the defect. See Figure 2.

$$y^2 - h^2 = \frac{Q}{\Pi k} \ln (x/r_0) \qquad (7)$$

Assume complete drawdown of groundwater at point of defect 1 or h = 1.67. Find height of groundwater in trench at defect 2. For equation (7), r_o represents well diameter. For this example, r_o = 0.5/(2)(12) = 0.021 ft. S_m represents maximal drawdown.

$$y^2 - (1.67 \text{ ft}^2) = \frac{(0.0042 \text{ ft}^3\text{/s})}{\Pi\ (0.1164 \text{ ft/s})} \ln(100 \text{ ft}/0.021 \text{ ft})7 \text{ ft}^2) = 1.699 \text{ ft}$$

This is 0.029 feet higher than at defect 1.

Then, find velocity in soil (V_1) surrounding trench while defect 1 is active. From Equation (1):

$$V_1 - K_1(i)$$

$$= 0.000155\ (1.32/1.5) = 0.000136 \text{ ft/s.}$$

where hydraulic gradient along trench is average height of water table over defect (top of pipe) over distance from trench face to defect (center of pipe) or 1.5 ft.

Groundwater at defect 2 is 3 - 1.699 = 1.30 ft.

For length L, average h is (1.33 + 1.30/2) = 1.32 ft.

Then, solve for flow in trench between defects, Q_T

$$Q_T = V_1 dL$$

$$= (0.000136)(3)(100) = 0.041 \text{ ft}^3\text{/s} = 18.40 \text{ gpm}$$

Next, find Q1 into defect 1. Use Equation (3). Assume C = 0.60.

$$Q1 = (0.60) \frac{\Pi\ (0.5/12)^2}{4} \sqrt{2(32.2)(1.33)}$$

$$= (0.60)(0.00136) \sqrt{(64.4)(1.33)}$$

$$= 0.00755 \text{ ft}^3\text{/s} = 3.39 \text{ gpm}$$

Solve Equation (5)

$$Q = 1.89 \text{ gpm} + 18.40 \text{ gpm} - 3.39 \text{ gpm}$$

$$= 16.90 \text{ gpm}$$

Although 16.90 gpm is still in trench at defect 2, the flow at this defect will be reduced because of drawdown at defect 1. Flow will increase as head in trench rises with repair of defect 1.

The flow through defect 2 while defect 1 is active is,

$$Q_2 = (0.60)\left(\frac{\Pi(0.25/12)^2}{4}\right)\sqrt{2\ (32.2)(0.029)}$$

$$= (0.60)\ (0.000341)\ (1.367)$$

$$= 0.000280 \text{ ft}^3\text{/s} = 0.13 \text{ gpm}$$

Because of localized in trench drawdown from defect 1 only, 0.13 gpm leaks at defect 2. When defect 1 is repaired, the head in trench recovers to 1.33 ft over defect 2, and then,

$$Q_2 = (0.60)\left(\frac{\Pi(0.25/12)^2}{4}\right)\sqrt{(64.4)(1.33)}$$

$$= (0.60)\ (0.000341)\ (9.255)$$

$$= 0.00189 \text{ ft}^3\text{/s} = 0.85 \text{ gpm}$$

Thus, fixing defect 1 will result in 0.85 - 0.13 = 0.72 gpm migrating to defect 2. The repair of defect 1 alone will result in a net reduction of 3.39 - 0.72 = 2.67 gpm or 79 percent of the original flow at defect 1.

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