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DESIGN OF INFILTRATING BASIN

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Abstract: Design of storm water storage basin must take both surface infiltrating flow and subsurface seepage flow into consideration. This paper suggests that for an on-site storm water disposal facility, the basin storage volume shall not exceed the soil pore storage capacity. On the other hand, for a long-term groundwater recharging basin, the subsurface geometry at the basin site must be able to sustain the surface infiltrating water. To avoid a prolonged draining operation, an infiltrating basin must be designed with consideration of the soil pore storage capacity before the soil medium is saturated and the soil conveyance capacity after saturation. In this study, the potential flow model is applied to estimate the soil pore storage volume underneath the basin and to predict the conveyance capacity through the saturated soil medium between the basin and the local groundwater table. The potential flow model for infiltrating water flow provides a quantifiable basis to define the soil constraints and to compare various alternatives at the basin site.

Key Words: storm water, basin, BMP's, infiltration, seepage, groundwater

INTRODUCTION

Under the Federal Clean Water Act, many best management practices have been developed for on-site disposal of storm water. As a storm water quality control facility, an infiltration basin is often designed for micro events at the level of daily runoff, but not for the minor (5-year) or major (100-year) events (Guo and Urbonas in 2002, Guo 2002). When the basin is loaded with storm water, the soil medium between the basin and the groundwater table will first undergo a storage process in which the soil water moisture varies from an unsaturated to a saturated condition. As soon as the infiltrating water reaches the groundwater table, the saturated soil medium will act as a conduit to pass the water flow. The conveyance capacity in a saturated soil medium depends on the hydraulic gradient and the soil conductivity. If the underground seepage flow through the soils cannot sustain the surface infiltrating water, the soil-water system will be backed up and a water mound will begin to build up. The shape and growth of water mound depend on the rate of infiltrating flow, size of the basin, and hydraulic properties of the soil mediums (Ferguson 1990, Guo 2001).

The soil hydraulic conductivity varies with respect to the water content in soils and can be related to its saturated value by the soil-water characteristic curve (Stankovich and Lockington 1995). Modeling the infiltrating water through soils typically requires such a functional representation of soil hydraulic properties (Brook and Corey 1964). This study applies the concept of a constant hydraulic conductivity to the potential flow model by which the movement of the wetting front can be predicted and the saturated soil volume underneath the basin can be quantified. At a basin site, the potential flow model provides a simplified and useful approach to understand the soil constraints for the design and a quantifiable basis for site evaluation and alternative comparison.

CONVEYANCE CAPACITY IN SOILS

As illustrated in Figure 1, the infiltrating water begins with a vertical downward velocity through the unsaturated zone underneath the basin. As the soil water content increases, the diffusive nature of the wetting front results in flow movements in both vertical and lateral directions. As soon as the seepage flow reaches the local groundwater table, the soil medium beneath the basin becomes saturated and the seepage flow radially disperses into groundwater. Although many studies used the concept of potential function to investigate the vertical seepage flow and the associated water mounding effect (Hantuch 1968, Griffin and Warrington in 1988, McDonald et al. 1984), this study applies stream function to describe the movement of the seepage flow through the soil medium. With the consideration of vertical and radial movements, the potential flow model using stream function is developed for the infiltrating flow under a circular basin as (Guo, 1998 and 2001):

$$\psi = \pi \frac{f}{D} r^2 y \quad (1)$$

in which ψ = stream function, f = infiltration rate, D = vertical distance for infiltrating flow underneath the basin, r = radius of wetting front, and y = vertical distance above the groundwater table.

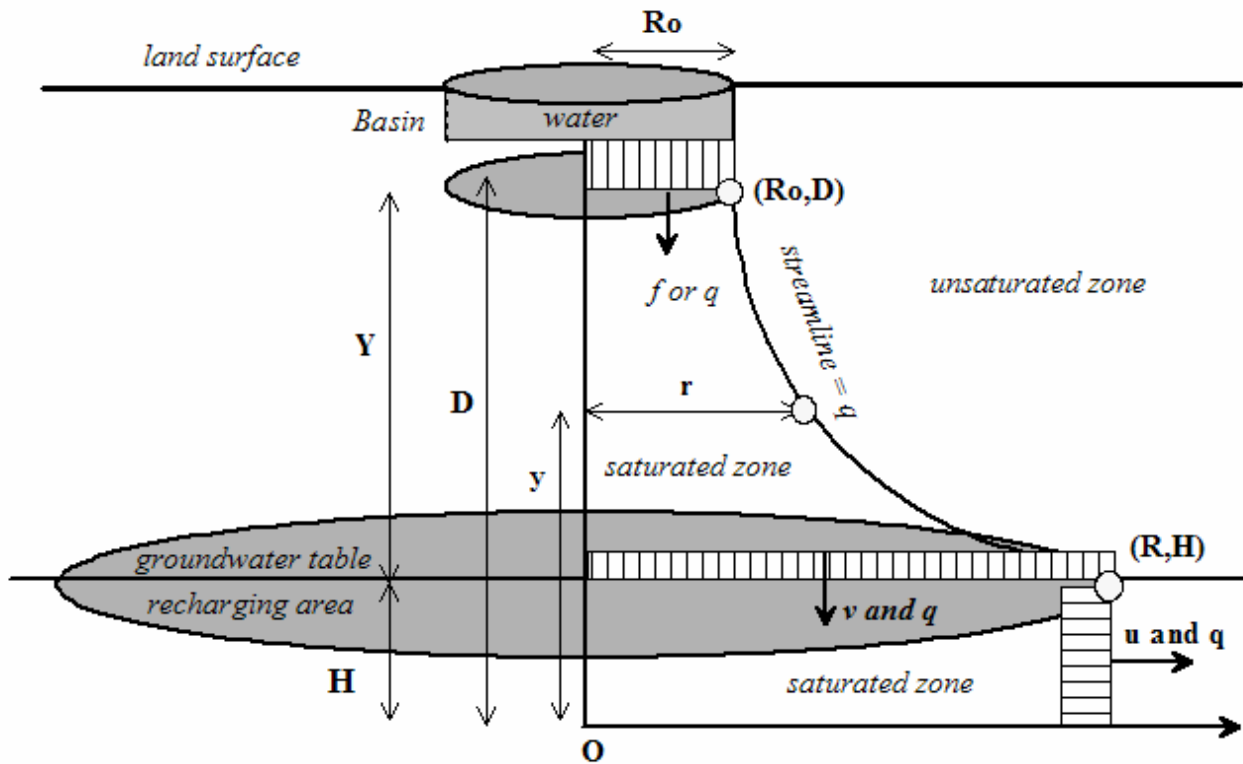


Figure 1 Illustration of Infiltrating Water

The physical meaning of stream function is the cumulative discharge. For this case, the values of stream functions around the bottom of the basin represent the cumulative release from the basin. The streamline through Point (R_o, D) must have a stream function equal to the total release from the basin as:

$$\psi_c = q = f\pi R_o^2 \quad (2)$$

in which q = infiltrating volume rate, R_o = basin radius. Between the bottom of the basin and the cross section at (r,y) in Figure 1, Eq 1 satisfies the principle of continuity and also describes the growth of the wetting front. Equating Eq 2 to Eq 1 yields

$$r = \sqrt{\frac{D}{y}} R_o \quad (3)$$

Applying Eq 3 to Point (R,H) on the groundwater table in Figure 1, the radius of the recharging circle is defined as:

$$R = \sqrt{\frac{D}{H}} R_o \quad (4)$$

Derivatives of Eq 1 with respect to y and r represent the velocity components in the flow field as:

$$u = \frac{f}{2} \frac{r}{D} \quad (5)$$

$$v = -f \frac{y}{D} \quad (6)$$

Under a steady state, the flow rate is constant through all sections in Figure 1. Along the vertical direction, the hydraulic gradient, i , can be approximated by unity, $i = -1$ (downward) when the soil suction is ignored (Morel-Seytous al et. 1990). According to the Darcy's law, the recharging flow velocity to the groundwater table is:

$$v = \frac{q}{\pi R^2} = -K_y \quad (7)$$

in which K_y = hydraulic conductivity in the vertical direction. Eq 7 must agree with the vertical velocity described by Eq 6 at $y=H$. Setting Eq 7 equal to Eq 6 yields:

$$D = \lambda_y H \quad (8)$$

and

$$\lambda_y = \frac{f}{K_y} \quad (9)$$

The recharge flow radially disperses into an upper thickness of the aquifer, with much almost stagnant water in the deeper portion of the aquifer (Bouwer et. al. 1999). In this study, such an active flow depth, H , below the initial groundwater table is estimated by the Dupuit-Forchheimer equation as:

$$q = \psi_c = \frac{K_r \pi}{\ln(R/R_o)} (D^2 - H^2) \quad (10)$$

in which K_r = hydraulic conductivity in the radial direction. In general, storm water infiltration basins are small in size and operated with a short loading period. Unlike the long term recharging basin, the height of a water mound under a small storm water retention basin decays toward the initial groundwater table. Under this condition, Eq 10 can be an approximation near the edge of the area of recharge, i.e. Point (R,H) in Figure 1. Eq 10 divided by the effective flow depth, H, yields the radial flow velocity that must be equal to the horizontal velocity described by Eq 4. As a result, the active flow thickness of aquifer is derived as:

$$\frac{H}{R_o} = \sqrt{\frac{\lambda_r \ln \lambda_y}{2(\lambda_y^2 - 1)}} \quad (11)$$

And

$$\lambda_r = \frac{f}{K_r} \quad (12)$$

In practice, the value of H is the smaller one between Eq 11 and the available thickness. Aided by Eq 8, the vertical flow depth, D, underneath the basin is

$$\frac{D}{R_o} = \lambda_y \sqrt{\frac{\lambda_r \ln \lambda_y}{2(\lambda_y^2 - 1)}} \quad (13)$$

To enhance the effectiveness of storm water disposal, the design infiltration rate is often chosen to be greater than the hydraulic conductivity, i.e. $\lambda_y > 1$ or $\lambda_r > 1$. However, the seepage flow underneath the basin depends on not only the soil hydraulic conductivity but also the subsurface hydraulic gradient. To sustain a steady state, Eq's 11 and 13 prescribe the required saturated depths in order to provide sufficient hydraulic gradients.

STORAGE CAPACITY IN SOILS

Under a steady state condition, the vertical movement of the wetting front is within the soil volume outlined by the streamlines. Aided by Eq 3, the incremental volume, dV , due to a movement of, dy , at depth, y , can be calculated as:

$$dV = \pi r^2 dy \quad (14)$$

Aided by Eq 3, Eq 14 is integrated from $y=D$ to $y=H$ as:

$$V_s = \pi D R_o^2 \ln\left(\frac{D}{H}\right) \quad (15)$$

in which V_s = saturated soil volume between the basin and the groundwater table. During the saturation process, the soils begin with an initial water content, θ , and end up with the final water content equal to the porosity, θ_s . As a result, the soil storage volume beneath the basin is:

$$V_w = (\theta_s - \theta)V_s \quad (16)$$

When the basin stores storm water more than the soil storage capacity beneath the basin, the draining process begins with the storage process to saturate the soil and then continues with the conveyance process to recharge the groundwater.

DESIGN EXAMPLE

The challenge in storm water retention design is to cope with the huge water volume. Both soil conveyance and storage capacities depend on the vertical distance between the basin and the local groundwater table. If the basin stores a water volume less than the subsurface soil storage capacity by Eq 16, the draining process is essentially to saturate the soil medium; otherwise the effectiveness of draining relies on the subsurface geometry below the basin. It is necessary to make sure that adequate hydraulic gradients exist to sustain the infiltrating flow rate. This paper presents an example to demonstrate how to determine the storage capacity at a site. The surface infiltration rate for the example is 1.5 inch/hour and the soil hydraulic conductivity is 1.0 inch/hour. The soil porosity is 0.35 at the site and the initial water content is 0.10. Assuming that the underground environment is homogenous and isotropic, therefore $\lambda_r = \lambda_y = 1.5$ for this case. By Eq's 11 and 13, the vertical flow distance, D, and the groundwater active thickness, H, are calculated as:

$$\frac{D}{R_o} = 0.74 \quad (17)$$

$$\frac{H}{R_o} = 0.49 \quad (18)$$

The vertical distance, Y, between the basin and the local groundwater table is the difference between D and H as:

$$\frac{Y}{R_o} = \frac{D - H}{R_o} = 0.25 \quad (19)$$

At the basin site, the vertical distance, Y, to the groundwater table is known. Table 1 is a comparison among the cases with a different vertical distance, Y. To be conservative, the basin storage volume shall not exceed the soil storage capacity beneath the basin (Guo and Hughes 2001). Otherwise, the soil medium has to serve as a conduit to continuously pass the seepage flow and may develop a water mound to back up the flow system. Considering the soil pore storage volume as basin volume, the water depths are calculated in Table 1. This method agrees with the general practice that infiltrating basins shall be wide, flat, and shallow in depth.

Vertical Distance Y feet	Basin Radius Ro feet	Vertical Flow Distance D feet	Groundwater Active Thickness H feet	Soil Saturation Volume Vs cubic ft	Soil Storage Capacity Vw cubic ft	Water Depth In Basin feet
	Eq 19	Eq 17	Eq 18	Eq 15	Eq 16	
5.0	20.0	14.8	9.8	7663.1	1915.8	1.52
10.0	40.0	29.6	19.6	61305.1	15326.3	3.05
15.0	60.0	44.4	29.4	206904.7	51726.2	4.57

Table 1 Soil Conveyance and Storage Capacities for $\lambda_r = \lambda_y = 1.5$

CONCLUSIONS

Urban water environment is an increasing concern to many metropolitan areas. Retention basins are an effective approach to reduce pollutant levels in storm runoff. Considering the uncertainties in estimating surface and subsurface hydrologic parameters, a basin is often designed with insufficient information. After installation, the basin may not be maintained as scheduled. As a result, it is necessary to apply a conservative approach to design a storm water storage basin.

In practice, the loose soil texture on the surface tends to have a higher infiltrating rate than the soil conductivity below the basin, i.e. $\lambda_r > 1.0$ or $\lambda_y > 1.0$. In order to sustain the continuity between the surface and subsurface flows, this paper presents a method, Eq's 11 and 13, to determine the minimum vertical depth required underneath the basin. If the vertical distance from the basin bottom to the groundwater table is greater than required, the subsurface geometry beneath the basin is able to sustain the infiltrating water. Otherwise, water mounding may back up the soil-flow system and standing water appears in the basin for a prolonged draining time.

The operation of soil infiltration is a transfer of water volume from the surface basin to the underground. In practice, the soil medium is likely to be nonhomogeneous and nonisotropic. With many uncertainties in the assessment of soil conveyance capacity, it is advisable that the basin is designed with a storage volume not to exceed the available pore volume in the soils by Eq's 15 and 16. As a rule of thumb, one foot of water may fill up the pore volumes in four feet of soils.

The potential flow model is applicable to the designs of storm water retention basins, highway infiltration trenches, infiltration ponds, percolation pavements, vegetable beds etc.. The potential flow model does not require detailed site specifics. It is simple in use and provides reasonable assessments on water mounding impacts. It can be a useful tool at the planning stage when little design information is available, but it does not replace the necessity of more complicated groundwater flow modeling studies to refine the predictions.

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