Developing a Simple Approach for Estimating the Infiltration Capacity of Infiltration Gutters

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Abstract

Infiltration gutters are often applied to address the urban hydraulic impact resulting from rapid urbanization. Despite their applicability in many of Asia’s fast growing middle-sized cities, their characteristics and performance, however, have not been properly understood for supporting sound design. To this end, this study assessed their performance and proposed a simple approach based on Darcy’s law for estimating the infiltration capacity of an infiltration gutter. Permeable-brick infiltration gutters were constructed and tested on-site. Water infiltrated through three scenarios, i.e., the surfaces of two vertical sides (NFS-2S), the bottom (NFS-B), and three faces (NFS-3S) of the gutter, which were measured under steady state conditions. Test results indicate that specific infiltration area per unit length ($A_u.s$), denoting the final infiltration rate divided by the saturated hydraulic conductivity of the soil, and the designed water depth ($H$) are linearly dependent on each other for NFS-2S and NFS-3S but not for NFS-B. Experimental results also indicate that when the bottom of the gutter is clogged, the gutter still retains about 93% of its infiltration capacity. Based on these on-site tests, this study thereby developed a simple tool using Darcy’s law to design infiltration gutters.

Keywords: urban hydraulic impact; infiltration gutter; permeable-brick

1. Introduction

Green Building commonly refers to environmentally friendly buildings, which conserve energy, water, etc. In 2001, the Executive Yuan, the highest administration office in Taiwan, passed the Green Building Promotion Regulation advocating that the Green Building Evaluation System (GBES) should be applied during the initial design stages of public buildings. The GBES consists of nine rating criteria to measure a building’s greenness, i.e., Biodiversity, Greenery, Water Retention, Water Saving, Energy Saving, CO₂ Emission Reduction, Waste Reduction, Indoor Environment Improvement, and Sewage and Garbage Reduction (ABRI, 2003). Among them, the Water Retention rating criterion identifies the water retention capability between pre- and post-development conditions, for easing the hydraulic impact resulting from urban development.

Urbanization, which enlarges the impervious surface, typically has multiple impacts on stream systems. For example, the increased peak stream flows caused by urbanization increase channel incision, bank erosion, and sediment transport (Konrad et al., 2002). Another impact is the reduction of infiltration, which lessens groundwater recharge and increases pollutant loads to streams (Linsley et al., 1992; Winter et al., 1998; Sieker et al., 1998; Finkenbine et al., 2000). Infiltration gutters, trenches, ditches, ponds, ecological ponds, buried porous pipes, and porous pavements are all proposed by Water Retention rating criteria in the GBES offering solutions to the problems of increased stormwater runoff and decreased groundwater recharge. Among them, the infiltration gutters constructed beside roads or buildings are simple and inexpensive. In Taiwan, infiltration gutters are commonly constructed using matrices of permeable-brick and redbrick with sand-, gravel- or soil-filled joints. These joints allow stormwater to infiltrate the soil and thereby play a substantial role in mitigating the impact of stormwater runoff caused by urban development (Watanabe, 1995). Infiltration gutters, when combined with urban drainage systems, are particularly applicable in many of Asia’s fast growing middle-size cities.

Infiltration pond capacity and long-term monitoring
of infiltration trenches are issues related to infiltration facilities which have been widely discussed (Guo, 1998; Guo, 2003; Majed et al., 2000; Warmaars et al., 1999). Seki et al. (2004) developed a simple method for estimating rainwater percolation from a buried container into a vadose zone based on a field experiment. Reynolds et al. (1985) demonstrated that the performance of infiltration wells can be expressed as a comprehensive coefficient based on the geometric shape of cylinder infiltration well and water depth, with no direct relationship to soil characteristics. However, there have been few studies of infiltration gutters which are more applicable in high-density cities. Moreover, the hydraulic theory and on-site tests have not been properly integrated, and the characteristics of infiltration gutters remain undefined. Architects and engineers need more information to gain a good understanding of infiltration gutters, which would allow them to then make sound decisions and good designs. For this, on-site tests should be conducted. The purpose of this study is threefold: first, to explore the characteristics and performances of various types of infiltration gutters based on on-site tests; second, to propose a measurement for estimating the infiltration capacity of permeable-brick infiltration gutters using Darcy’s law; and lastly, to develop a simple tool for designing infiltration gutters.

2. Study Design and Site
2.1 Study design and experimental Site
The primary element in this study was the construction of an infiltration gutter. Based on opinions from experienced contractors and an evaluation of available gutter designs, a permeable-brick infiltration gutter was selected for analysis. The gutter was constructed at the experimental site. The experimental site was located at the entrance of the Hsintien office of the Water Resources Agency of the Ministry of Economic Affairs. The facility is surrounded by a gated fence which is locked during non-business hours, thus, minimizing any risk of vandalism.

2.2 Soil properties investigation
Three soil samples, each taken one-meter below the soil surface, were harvested from three different locations at the experimental site. Based on the Unified Soil Classification System (USCS), these soil samples were categorized as low plastic silt (ML). The grain-size distributions of the soil materials were extremely consistent but not well graded. A constant head test using a Guelph permeameter was employed to estimate the hydraulic conductivity of saturated soil.

2.3 Infiltration gutter construction
According to current national construction regulations, a gutter should be larger than 30 cm wide and 40 cm high. The experimental on-site infiltration gutter was thus designed to be 35 cm wide and 45 cm high. The total length was 550 cm, due to space limitations. The permeable bricks, manufactured on-site, were of two different sizes: \(L500\text{mm} \times W500\text{mm} \times H50\text{mm}\) and \(L200\text{mm} \times W100\text{mm} \times H50\text{mm}\). The larger bricks were installed in the gutter bottom and the smaller bricks were used to construct the vertical sides of the gutter. The permeable bricks were made of Portland type I cement with a grain-size distribution between 5–20 mm, water, and adhesive solidification. The grain-size distribution of the backfill layer ranged from 20 to 30 mm. The compressive strength of the permeable bricks was roughly 162 kgf/cm², with a permeable coefficient of about \(2.1 \times 10^{-1}\text{cm/sec}\). Fig.1. shows the cross-sectional profile and bird's eye view of the gutter.

2.4 Water supply system
Water for the experiment was supplied by two sources: rainwater collected from the rooftop of a nearby parking garage; and, existing water supply system pipelines. Water was recycled through an underground storage tank with a storage capacity of 2.4 tons.

3. Theoretical Analysis and Development
3.1 Estimation of saturated hydraulic conductivity for on-site soil
The saturated hydraulic conductivity parameter represents the ability of soil to convey water. Reynolds et al. (1985, 1987) developed a numerical model for water infiltration from a cylindrical well under a constant water depth to calculate saturated hydraulic conductivity. The saturated hydraulic conductivity of
soil \( (K_{soil}) \) can then be expressed as

\[
K_{soil} = \frac{CQ - 2\pi h^2 \phi_m}{2\pi h^2 \left(1 + \frac{C}{2} \frac{a}{h}\right)}
\]

where \( C \) is shape factor; \( Q \) is the final infiltration volume; \( h \) is the water depth in the well under a steady state; \( a \) is the radius of an infiltration well; \( \phi_m \) is the flux potential for the unsaturated zone; and, \( l \) is the distance between the selected point along the line source and the water surface of an infiltration well.

If flux potential is excluded from Eq. (1) and, assuming that \( l \) equals 0, Eq. (1) transforms into a renowned Glover solution. Obtaining the \( K_{soil} \) value with the Glover solution is easier than with the Reynolds solution. The Glover solution is therefore used to estimate \( K_{soil} \). Eq. (1) can then be written as

\[
A_s = \left[ \frac{2\pi h^2}{\sinh^{-1} \left( \frac{h}{a} \right) - \left( \frac{a}{h} \right)^2 + 1} \right]^{0.5} + \frac{a}{h}
\]

where \( A_s \) is the specific infiltration area defined as the final infiltration volume \( (Q) \) divided by the saturated hydraulic conductivity of the soil \( (K_{soil}) \).

Eq. (3) demonstrates that \( A_s \) is solely related to the geometric shape of the cylindrical infiltration well and the water depth and that \( A_s \) has no direct relationship with soil characteristics.

\[Q = Q_{BOTTOM} + 2Q_{SIDE} \]

Fig. 2. Schematic Diagram of the Flow Path of an Infiltration Gutter (a) Theoretical, (b) Approximated

3.2 Estimation of the infiltration capacity of an infiltration gutter

The infiltration gutter is comprised of two parts: the drainage gutter made of highly permeable material (part A of Fig. 2.(a)) and the temporary storage part beneath part A made of backfill material (part B of Fig. 2.(a)). Typically, the saturated hydraulic conductivity of the backfill material \( (K_{gravel}) \) is substantially larger than that of the underlying soil \( (K_{soil}) \). Therefore, during a steady state, the theoretical water level in the infiltration gutter can be shown in Fig. 2.(a). If the declination of the water level in part B is neglected, the infiltration mechanisms of the infiltration gutter can be estimated as shown in Fig. 2.(b). Therefore, at a steady state, the infiltration capacity of an infiltration gutter depends on the infiltration surface, water depth and saturated hydraulic conductivity of the underlying soil \( (Chin, 2000) \). The infiltration capacity at a steady state \( (Q_{steady}) \) is therefore expressed as

\[Q_{steady} = Q_{BOTTOM} + 2Q_{SIDE} \]

In Eq. (4), \( Q_{BOTTOM} \) represents water infiltrated from the gutter bottom and \( Q_{SIDE} \) is water infiltrated from the vertical sides of the gutter; both values can be estimated using Darcy’s law and expressed as

\[Q_{BOTTOM} = K_{soil}A_{BOTTOM\ perc} \]

\[Q_{SIDE} = 0.5K_{soil}A_{SIDE\ perc} \]

where \( A_{BOTTOM\ perc} \) is the area of infiltration from the bottom and \( A_{SIDE\ perc} \) is the area of infiltration from the vertical sides. If the total length of an infiltration gutter is \( L \), the theoretical specific infiltration area per unit length \( (A_{h_s\ perc}) \) can be expressed as

\[A_{h_s\ perc} = \frac{Q_{steady}}{KL} = \left[ b + 0.4(H + d) \csc \beta \right] \]

where \( H \) is the designed water depth of an infiltration gutter; \( d \) is the thickness of the backfill layer beneath an infiltration gutter bottom; \( b \) is the width of an infiltration gutter; and, \( \alpha \) is the angle between the horizontal and incline surfaces of the backfill beneath the vertical sides of the gutter.

Eq. (7) estimates the theoretical infiltration capacity of an infiltration gutter and shows that the theoretical specific infiltration area per unit length is related to the geometric shape of the infiltration gutter, not the soil characteristics. For actual infiltration area per unit length \( (A_{h_s}) \), the required correction factor can be expressed as

\[A_{h_s} = \left[ C^*(H) \right] \left[ A_{h_s\ perc} \right] \]

where \( C^*(H) \) is a correction factor and \( \beta \) and \( \gamma \) are constant values. These values can be obtained through on-site tests.

4. Experimental Design and Procedures

4.1 Saturated hydraulic conductivity of underlying soil

To estimate the saturated hydraulic conductivity of the underlying soil, three holes of 6 cm in diameter and 60 cm in depth were dug. The constant head method was applied to identify the final infiltration volume of various water depths; Eq. (3) was then used to calculate the average saturated hydraulic conductivity of the soil.

4.2 Final infiltration of the gutter

Infiltration characteristics of the soil at a given location can be obtained by performing an infiltrometer experiment on small areas. Double-ring infiltrometry is a commonly used experiment consisting of two
rings inserted into the ground while the water level in both rings is maintained at a specific level on the soil surface. The measurement of water volume is performed only on the inner ring. The experiment in this study employed the concept of double-ring infiltrometry to estimate the final infiltration volume of the gutter at different water depths. In this study, to prevent the spreading out of the water infiltrating into the inner apartment, the length of the inner ring apartment was 50 cm with 20 cm on each side. Water infiltration was measured in the inner apartment. Fig. 3. shows a schematic of the layout of the experiment. The amount and mechanism of water infiltration from the gutter bottom and vertical sides were investigated separately. The experimental procedure includes the following seven steps:

Step 1: Select the bottom or vertical sides as the study object and seal the other sides with clay and an impermeable plastic sheet. If all three sides of the gutter section are being examined, this step is omitted.

Step 2: Open the flow control valve and begin infusing water into the inner and outer ring apartments.

Step 3: Maintain the same water levels for both inner and outer apartments.

Step 4: Record the stable water depth using a water level meter in the inner apartment.

Step 5: Measure the average final infiltration capacity of the inner apartment when the water depth is stable.

Step 6: Increase the infusing water rates and repeat steps 3–5 for various water depths. A minimum of five different water depths is required.

Step 7: Estimate the specific infiltration area of the gutter per unit length for different water depths.

5. Data Analysis and Discussions

The saturated hydraulic conductivity coefficient of soil at 60 cm beneath the surface was measured on site and estimated as $5.9 \times 10^{-3}$ cm/s. However, the soil property investigation in Section 2.2 identified the soil as ML with a saturated hydraulic conductivity coefficient in the range of $10^{-5}$–$10^{-7}$ cm/s (Bardet, 1997). The difference between these two values is significant. Close examination of the on-site soil shows that the surface layer consists primarily of backfill, which has a higher porosity than that of ML. This finding indicates that the surface-layer soil has a higher saturated hydraulic conductivity coefficient than that of the deeper soil. This phenomenon is typical of most construction sites in Taiwan. Therefore, on-site measurements of the saturated hydraulic conductivity coefficient of soils at construction sites are more accurate than estimations based directly on sample soils.

Three scenarios were considered for the infiltration experiment of the gutter: (1) infiltration from the bottom and the two vertical sides (NFS-3S); (2) infiltration from the bottom only (NFS-B); and, (3) infiltration from the two vertical sides (NFS-2S). Experimental results are discussed in this order.
(1) NFS-3S scenario
To identify the relationship between the specific infiltration area per unit length and water level, nine different water depths ranging from 3.3 to 24.6 cm were observed. These relationships (Fig. 4) can be expressed as

\[ A_{u.s} = 176.41 \ H \quad R^2 = 0.999 \]  \hspace{1cm} (9)

where \( A_{u.s} \) is the specific infiltration area per unit length; \( H \) is the designed water level of the infiltration gutter; and, \( R^2 \) is the coefficient of determination.

(2) NFS-B scenario
Twelve different water depths ranging from 3.3 to 27.2 cm were observed. Their relationships (Fig. 5) can be expressed as

\[ A_{u.s} = 49.95 \ H^{0.75} \quad R^2 = 0.999 \]  \hspace{1cm} (10)

(3) NFS-2S scenario
Five different water depths ranging from 10.3 to 27.1 cm were observed. Their relationships (Fig. 6) can be expressed as

\[ A_{u.s} = 164.41 \ H \quad R^2 = 0.999 \]  \hspace{1cm} (11)

Based on the principle of continuity, the amount of water infiltrated from the surface of an infiltration gutter is the sum of water from the bottom and two vertical sides, as shown in Eq. (4). However, the measurement results in this study demonstrate that the amount of water infiltrated from NFS-3S is less than the sum of water infiltrated from NFS-B and NFS-2S at all water depths. To further investigate the relationships between the water infiltrated from the bottom and vertical sides, the \( A_{u.s} \) values for NFS-B and NFS-2S were each divided by the \( A_{u.s} \) value of the NFS-3S; these values were then plotted against various water depths (Fig. 7). According to the authors’ findings, the ratios of water infiltrated from the bottom of the gutter to total water infiltration are high when water depths are low. As water depth increases, the ratios decrease and finally reach a constant value of roughly 38%.

The amount of water infiltrated from the two vertical sides accounts for 93.2% of the total amount of water infiltration; and there is a constant value for various experimental water depths in the gutter. In the case of NFS-2S, water infiltrating through the vertical sides accumulated in the backfill layer, as the hydraulic conductivity of the backfill layer is greater than that of the underlying soil; that is, the accumulated water eventually flows to the backfill layer at the bottom. This increases the infiltration surface. This is very similar to the flow mechanism at work in the case of NFS-3S. Moreover, this makes the ratios of the \( A_{u.s} \) values for NFS-2S and NFS-3S approach unity. Therefore, the two vertical sides play a primary role in the infiltration process of a gutter. The experimental results also reveal that when the bottom of the infiltration gutter is clogged, the gutter still maintains about 93% of its infiltration efficiency.

If the designed water depth and saturated hydraulic conductivity of the underlying soil are known, the infiltration capacity of an infiltration gutter at the steady state can be estimated by Eq. (7). In addition to water depth, the width of an infiltration gutter is also a factor that influences experimental results. If the infiltration mechanism is the same for infiltration gutters of various widths, the specific infiltration area per unit length can be obtained by combining Eq. (7) and (8); and, thus, the correction factor \( C(H) \) of the gutter may be expressed as

\[ A_{u.s} = 100.107(1-e^{-0.589H})(0.701+b+1.004H) \]  \hspace{1cm} (12)

Eq. (12) can be employed to estimate the actual specific infiltration area per unit length for various infiltration gutters designed with different water depths and widths. Fig. 8 shows the relationships among \( A_{u.s}, H \) and \( b \).
6. Summary and Conclusions

Constructing infiltration facilities in dense urban areas is a significant countermeasure to reduce effective precipitation, which has a direct connection with downstream drainage systems. The strategy of hydrologic and hydraulic disconnectivity can be used to control runoff timing, reduce runoff volume, increase water infiltration, and provide water quality benefits.

This study investigated the performance of a permeable-brick infiltration gutter from the perspectives of initial design and infiltration characteristics. The specific infiltration area per unit length, which is defined as the final infiltration volume divided by the saturated hydraulic conductivity of the soil, and water depth are linearly dependent on each other for NFS-2S and NFS-3S but not for NFS-B. The ratio of water infiltrated through the bottom of the gutter to the total amount decreases and reaches a constant value as water depth increases. Conversely, water infiltrated through both vertical sides of the gutter plays a primary role as water depth increases; that is, if the gutter bottom is clogged, the gutter retains 93% of its designed infiltration capacity. All regression equations established in this study can serve as a basis for future infiltration gutter design. When the saturated hydraulic conductivity of underlying soil at a construction site is known and the size and depth of the gutter are also known, the steady infiltration capacity of the infiltration gutter can be estimated. This simple method provides architects and engineers with an effective tool when designing infiltration gutters.

Despite these generally favorable results, uniformly good performance cannot be guaranteed in all cases. Each experimental site has particular soil conditions, which may mask potential consequences of changes to infiltration over time. Despite this acknowledged limitation, the authors believe that these results verify the value of infiltration gutters and their long-term suitability in dense urban environments.

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