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A Simple Estimation of Excess Rainwater Percolation from a Buried Container into a Vadose Zone

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Abstract

This study evaluated the performance of a rainwater utilization system. Excess rainwater is drained from rooftops into an underground container from which the water infiltrates from the base and sides into the surrounding soil of a vadose zone. The saturated hydraulic conductivity of the soil where this system was used was very low at the surface and higher in the deeper layer where the container was located. A simple method was proposed to estimate the steady recharge rate of excess rainwater from the buried container into the surrounding soil of the vadose zone. By modifying the steady recharge equation, which is widely used in the theory of the Guelph Permeameter, a steady recharge rate from the container was calculated from the measured value of saturated hydraulic conductivity and the size of the container.

Key words : Rainwater percolation, Rainwater utilization, Steady recharge, Hydraulic conductivity, Buried container

1. Introduction

Rainwater utilization is attracting a great deal of attention, especially among people living in regions where excess rainwater is available. In some cases the collected rainwater is stored in underground containers for use in daily life and emergency. Excess rainwater is percolated to the surrounding unsaturated soil to avoid inundation and surface runoff of rainwater. Some people also expect that the recharge of groundwater may prevent the lowering of the ground level. When the rainwater exceeds the capacity of the buried water tank, the management of the overflow is crucial for the efficiency of a rainwater collection system.

The potential of a storage system that captures overflow from the buried tank strongly depends on the water retentivity and permeability of the soil of the surrounding vadose zone. In the 16th Century, people living on the Aso plateau in western Japan dug rainwater drainage ditches around their residences (Japanese Association of Groundwater Hydrology 2001). The National Institute of Civil Engineering of the Japanese Ministry of Construction implemented a system to recharge groundwater by collecting excess rainwater into buried porous pipes, which drains the water into the surrounding unsaturated soil zones and, eventually, into the groundwater (Ishizaki 1985). The draft of the “Manual on the investigation and planning of a rainwater percolation facility,” which was edited by the Society of the Rainwater Percolation Facility in 1995, provides information on percolation ditches and trenches, U-ditches, and pavement. However, the manual did not provide information for estimating the rates of infiltration from a water container into the surrounding unsaturated soils.

The objective of this paper is to demonstrate a simple method for estimating the excess rainwater percolated from an underground container into the surrounding soil of a vadose zone.

2. Materials and Methods

2.1 Study Site

The study site is located at Yachiyo City, Chiba Prefecture, Japan. Boring tests revealed that a dressed soil layer of about 1 m covers the Kuroboku soil layer of 0.2 to 0.5 m thickness. Below the Kuroboku soil layer is a Tachikawa loam layer of 1 to 3 m thickness. Both the Kuroboku soil and Tachikawa loam are Andosol, and they are known as Kanto loam.

2.2 Soil Profile Measurement

A 2-m soil pit was dug, and a soil profile was recorded. The profile of soil hardness was measured *in situ* with the use of Yamanaka soil hardness meter, which is widely used in Japan. The empirical relationship between the reading of the Yamanaka soil hardness meter and the soil hardness for the Kuroboku soil (Watanabe, 1992) was used for obtaining soil hardness values. Undisturbed cylindrical cores of 5-cm diameter and 5-cm height were taken to measure the saturated hydraulic conductivities, dry bulk densities, particle densities, and water content. Saturated hydraulic conductivities were measured by using the falling-head method with these undisturbed cores. *In situ* saturated hydraulic conductivities were determined with a Guelph Permeameter (Reynolds and Elrick, 1987). In every measurement of the Guelph Permeameter, the saturated hydraulic conductivity and the matric flux potential were determined by least-squares method by using three steady depths (5, 10, 15 cm) measurement (Reynolds and Elrick, 1987). In the calculation of Guelph Permeameter, proportionality parameter, C, was determined by equation (3) using b_1, b_2 and b_3 values of loam soil in Table 1.

Table 1 Parameters for Equation (3) (after Zhang, 1998)

Soil texture	b_1	b_2	b_3
Sands	2.074	0.093	0.754
Structured loams and clays	1.992	0.091	0.683
Unstructured clays	2.102	0.118	0.655

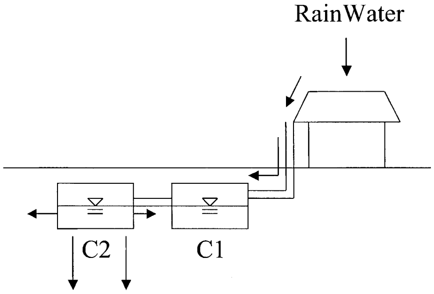

Fig. 1 Schematic diagram of a rainwater infiltration system.

2.3 Buried Container for Excess Rainwater

The rainwater infiltration system (Fig. 1) is briefly described. Rainwater flows from a rooftop to the first buried storage container (C1). The first container preserves 3 m^3 of rainwater, and, when the rainwater exceeds this volume, it flows to a second buried container (C2). The rainwater in the second container infiltrates into the soil from its base and permeable walls. A method will be shown here for estimating the recharge rate from the second container to the vadose zone ; the second container is referred to as “the container” or “the cubic container” in this paper. This system uses excess water to recharge groundwater instead of just draining the excess water into a drainage pipe. At the study site, the percolation system container is buried at a depth of 1 to 2 m and drains into the Tachikawa loam layer.

2.4 Method of Estimation

2.4.1 Assumptions

A simple method is described to estimate the percolation from a cubic container by calculating the percolation rate from a cylindrical container with an identical volume, i.e., the same base area and the same height. Two assumptions are made here. The first is that the recharge rate from a cubic container and a cylindrical container is nearly equal when the area of the base of each container is identical. The second is that the matric flux potential is negligible.

2.4.2 Procedure

Reynolds and Elrick (1987) developed a numerical model of infiltration from a cylindrical well with a constant pressure to calculate saturated hydraulic conductivity using the Guelph Permeameter method. According to their theory, a steady recharge from a cylindrical well into uniform and unsaturated soil is expressed as

$$Q=\frac{2\pi H^2 K_s}{C}+\pi a^2 K_s+\frac{2\pi H\phi_m}{C} \qquad (1)$$

where Q (m^3 s^{-1}) is the steady recharge, K_s (m s^{-1}) is the saturated hydraulic conductivity, H (m) is the steady depth of water in the well, a (m) is the well radius, ϕ_m (m^2 s^{-1}) is the matric flux potential, and C is a dimensionless proportionality parameter primarily dependent on the H/a ratio. The first term on the right hand side of Equation (1) expresses flow out of the sidewall of the well, the second term expresses flow from the base of the well, and the third term expresses the unsaturated component of the flow.

The matric flux potential, ϕ_m, is defined by

$$\phi_m=\int_{\phi_i}^{0} K(\phi)d\phi\ ;\ \phi_i\leq\phi\leq 0 \qquad (2)$$

where ϕ (m) is the soil water pressure head, ϕ_i (m) is the initial pressure head in the soil surrounding the well, and $K(\phi)$ is the unsaturated hydraulic conductivity (m s^{-1}) at the pressure head of ϕ.

Zhang (1998) provided empirical formula to describe C from the data calculated numerically by Reynolds (1986):

$$C=\left(\frac{H/a}{b_1+b_2H/a}\right)^{b_3} \qquad (3)$$

where the values of b_1, b_2, and b_3 are shown in Table 1.

Based on this theory, a simple method is shown for calculating the recharge rate from a cubic container, (i.e., well), with a base area of S (m^2). According to the first assumption, the steady recharge Q from the container is equal to the steady recharge from a cylindrical well with an identical base area, where

$$S=\pi a^2 \qquad (4)$$

By solving this equation with a, substituting it into Equation (3), substituting the value of C into Equation (1), and assuming $\phi_m=0$, the following equation is obtained:

$$Q=\left[2\pi H^2\left(\frac{b_1}{H}\sqrt{\frac{S}{\pi}}+b_2\right)^{b_3}+S\right]K_s \qquad (5)$$

When the values of K_s, S, H, b_1, b_2, and b_3 are given, the value of Q can be calculated, and the steady recharge from the container using Equation (5) can be estimated.

3. Results and Discussion

3.1 Soil Profile

From the observation of the soil pit, from the surface to 0.2 m was a dressed gravel layer; 0.2 to 0.95 m was a dressed soil layer; the Kuroboku soil layer was 0.95 to 1.2 m from the surface; and the Tachikawa loam layer, at the bottom of the pit, was from 1.2 to 2.0 m. The profile of the soil hardness and volumetric percentages of the solid, water and gas phases are shown in Fig. 2. As shown by the profile of the soil hardness, the soils were remarkably harder at the surface 0.5-m layer and at the 1.7–2.0 m layer than at the layer of 0.5 to 1.7 m. The solid ratios of the dressed soils were 40 to 45%, and those of Kuroboku soil and Tachikawa loam were 19 to 21%.

Saturated hydraulic conductivities measured *in situ* by the Guelph Permeameter and the falling-head method with undisturbed core samples are shown in Fig. 3. Each of the core sample values is the logarithmic means of five replicated samples. The saturated hydraulic conductivities of the soil surface, i.e., the dressed soil layer, were in the order of 10^{-10} m s^{-1}. The very low value of K_s in the dressed soil layer is because of extensive compression of the surface soil to make a rigid ground for

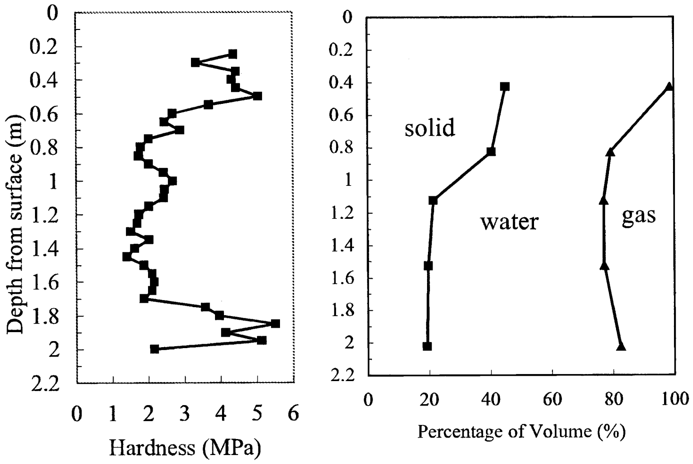

Fig. 2 Soil hardness and volumetric percentages of solid, water and gas phases.

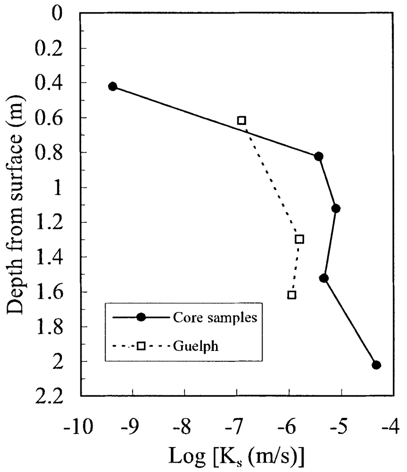

Fig. 3 Saturated hydraulic conductivity, K_s, measured by the falling-head method with undisturbed core samples and the Guelph Permeameter *in situ.*

construction. The saturated hydraulic conductivities increased dramatically at a depth between 0.8 and 1.5 m from the surface to the order of 10^{-6} m s^{-1}, and they increased to the order of 10^{-5} m s^{-1} at a depth of 2 m. These results agree with the K_s value of about 10^{-5} m s^{-1} of the Tachikawa loam soil measured by Tada (1965). The bulk density of about 0.5 Mg m^{-3} in Tachikawa loam layer also agrees with the measurement of Tada (1965). This profile is useful to explain the merits of this infiltration system in this region because the rainwater does not percolate easily into soil if it falls directly onto the ground, where the K_s is very low ; however, when the rainwater flows to the underground and percolates into a much more permeable soil layer by this system, the rainwater is recharged much more easily because the K_s is higher.

The field saturated hydraulic conductivity measured by the Guelph Permeameter was lower than the laboratory saturated hydraulic conductivity measured by the falling-head method with undisturbed core samples from the depth of 1.3 and 1.6 m (Fig. 3). A possible reason of this is that we compacted the inner wall of the observation well when we dug a hole for the Guelph Permeameter. According to the Guelph Permeameter measurement, the matric flux potential was 1.5 $\times 10^{-7}$ m^2 s^{-1} at the depth of 1.3 m.

3.2 Calculation of the Recharge Rate

Parameters used for the calculation are shown in Table 2. By putting the values of b_1, b_2 and b_3 of loam in Table 1 and the parameters in Table 2 into Equation (5), the steady recharge rate was calculated as $Q = 7.80 \times 10^{-5}$ m^3 s^{-1}.

Table 2 Parameters used for the calulation

K_s	$5.0\times10^{6}\,\mathrm{m\,s^{-1}}$
S	$4.7\,\mathrm{m}^2$
H	$0.94\,\mathrm{m}$

3.3 Evaluation of the Model

3.3.1 Effect of the shape of the container

At first, we will evaluate the first assumption that the recharge rate from a cubic container and a cylindrical container is almost the same when the area of the base of each container is identical. It is reasonable to assume that the steady recharges from the bases of both wells are equal because each base area is equal, and, inevitably, the depths of stored water are equal in each well. On the other hand, the side areas of cubic and the cylindrical containers are different, so it may seem inappropriate to assume that the steady recharge from both sides of the wells is equal. Actually, simple geometrical mathematics indicates that the side area of the cubic container is about 12.8% larger than that of the cylindrical container. It is necessary to point out that the first assumption and resultant estimation of the first term of the right-hand side of Equation (1) may underestimate the recharge rate from side wall of the well, and it may be as much as 12.8% larger than the estimated value. From a practical viewpoint, it is better to underestimate than to overestimate the recharge rate because the underestimated value works as a minimum estimate of the percolation capacity of the container.

3.3.2 Effect of the matric flux potential

According to the value of the matric flux potential measured by the Guelph Permeameter, the third term on the right of Equation (1) is $1.74\times10^{-6}\,\mathrm{m^3\,s^{-1}}$, and it is only 2.2% of the recharge rate calculated. Therefore ignoring the matric flux potential is justified in the condition of the experimental site.

However, the matric flux potential depends on the initial water content and soil type. According to Reynolds and Elrick (1987), the matric flux potential component of Equation (1) increases in relative importance with decreasing well radius (a), with decreasing depth of ponding in the well (H), with finer soil texture, and with decreasing background soil wetness (decreasing ϕ_i). When applying this model to actual site, background soil wetness is a variable and the recharge rate calculated from Equation (1) is a function of the initial water content. Therefore a minimum estimate of the recharge rate can be obtained by assuming maximum initial water content. In this model, by assuming $\phi_m=0$, we get the minimum estimate of the recharge rate.

3.3.3 Technical notes

The K_s of the permeable wall of the container should be larger than the K_s of the surrounding soil. Otherwise, the steady recharge is determined by the K_s of the permeable wall, not by the K_s of the surrounding soil. Moreover, the K_s of the permeable wall may decrease with time by the effect of clogging, and therefore the system should be maintained by cleaning the permeable wall.

4. Conclusion

We showed a simple method to estimate excess rainwater percolation from a buried container into the surrounding soil of a vadose zone. In the study site where the rainwater infiltration system was used, the saturated hydraulic conductivities of the soil surface were in the order of $10^{-10}\,\mathrm{m\,s^{-1}}$, and they increased to the order of $10^{-6}\,\mathrm{m\,s^{-1}}$ at a depth between 0.8 and 1.5 m. They increased further to the order of $10^{-5}\,\mathrm{m\,s^{-1}}$ at a depth of 2 m. Using a K_s value of $5.0\times10^{-6}\,\mathrm{m\,s^{-1}}$, the steady recharge rate was calculated as $7.80\times10^{-5}\,\mathrm{m^3\,s^{-1}}$. In the model presented here, the effect of the matric flux potential was ignored. Ignoring the matric flux potential in the studied site was justified by the calculation that the matric flux potential was 2.2% of the recharge rate, but it must be noted that the matric flux potential becomes larger when the initial water content is smaller and when the soil texture is finer. The model presented here may underestimate the recharge rate because of two assumptions, and it gives a minimum estimate of the maximum possible recharge rate from the container. At actual construction site at Chiba prefecture, Japan, the model has been implemented successfully to estimate the rainwater percolation rate to groundwater.

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埋設型浸透升からの雨水浸透量簡易予測手法について

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要　旨

新しく開発された雨水利用システムの性能を評価した。この雨水利用システムは，屋根に降った雨水を地下に埋設された貯留タンクに一時的に貯め，貯留タンクから溢れた水を貯留浸透槽に導き，地下に浸透させる。貯留浸透槽は底面および側面からの余剰水を浸透させるよう設計されているため，浸透槽の処理能力を知るには，土中への浸透流量を計算する必要がある。この貯留浸透槽が埋設されている現場では，土壌表面の透水係数は非常に小さく，貯留浸透槽が埋設されている立川ローム層では透水係数が地表面に比べて大きいことが分かった。ゲルフパーミアメーターの解析に広く用いられている定水位円筒型井戸からの定常浸透流解析法を元にして，矩形浸透升からの定常浸透流簡易予測法を提案した。この予測法を用いて，土壌の透水係数と矩形浸透升の大きさを与えることで，定常浸透流量を計算することができた。

キーワード : 雨水浸透，雨水利用，定常浸潤，透水係数，埋設型浸透升

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