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Research Paper

Effect of soil hydraulic properties on water infiltration of containerised soil

Harianto Rahardjo[a,*], Nina Amalia[b], Jian De Wee[c], Eng Choon Leong[d], Lai Fern Ow[e], Puay Yok Tan[f]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Blk N1, #1B-36, 50 Nanyang Avenue, 639798, Singapore[1]
[b] Environmental Process Modelling Centre (EPMC), 1 Cleantech Loop, CleanTech One, #06-08, 637141, Singapore
[c] Compliance Officer, RHT Capital Pte. Ltd., 6 Battery Road, 049909, Singapore
[d] School of Civil and Environmental Engineering, Nanyang Technological University, Blk N1, #1C-80, 50 Nanyang Avenue, 639798, Singapore
[e] Centre for Urban Greenery and Ecology, National Parks Board, Singapore Botanic Gardens, 1 Cluny Road, 259569, Singapore
[f] Department of Architecture, School of Design and Environment, National University of Singapore, 4 Architecture Drive, 117566, Singapore

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ABSTRACT

The development of infrastructure in an urban city, such as road widening and building work, will inevitably result in the removal of trees. Therefore, innovative solutions such as containerised tree in the manner of increasing the portability of trees would be necessary to facilitate efficient transplanting in order to maintain a sustainable green urban environment. Differences in soil hydraulic properties between soil mixture and in situ soil naturally occur in tree planting, but this difference becomes more important in the use of container due to the limited tree root movement. The objective of this research was to examine the effects of soil hydraulic properties between the soils inside and outside of the container with focus being placed on moisture infiltration both in and out of the container. Field instrumentation and laboratory tests were carried out together with parametric study using numerical model. The results suggested that the higher the ratio between the saturated permeability of the soils inside and outside the container, the lower was the ability of water to flow in and out of the container.

1. Introduction

Singapore has numerous mature and majestic trees. The widespread greenery is a result of years of effort invested in nurturing street and park greenery. The achievement of such a lush landscape is the result of uninterrupted growth that allows trees to mature. The development of infrastructures in an urban city, such as road widening and construction works, will inevitably result in removal or relocation of some trees. Therefore, innovative solutions will be necessary to allow for greenery to coexist with urban redevelopment. One possibility lies in increasing the portability of trees that would facilitate efficient transplanting. The use of containers is one such option that will enable trees to be relocated from one place to another with minimal disturbance to the root system and thus allowing uninterrupted growth. Special attention to the designs of the container is needed to ensure that the wall of the container does not ultimately disrupt the growth of the tree. Another key consideration was to ensure that the container was able to retain sufficient moisture and at the same time, drain out excess moisture.

Excessive water inside the container or soil saturation may potentially cause waterlogging (ponding). Numerous studies on the effect of soil saturation on trees have shown that excessive moisture is detrimental to tree growth and thus, should be avoided. Coder (1994) summarized the studies and pointed out the major impact of waterlogging on tree growth. By having the pore spaces in soil filled with water, the amount of oxygen available in the soil for the roots become very limited. Such anaerobic conditions will result in increased plant stress and reduced growth. Poor root development can pose stability issue or tree toppling (Nicoll & Ray, 1996). In the long term, the tree will be unhealthy, structurally unsound, and may have to be removed. Similarly when insufficient water is retained by the soil, it weakens the trees and makes it more susceptible to insect and pathogenic attacks (McDowell et al., 2008). It also reduces the amount of nutrition that the tree can absorb which in turn, restricts growth and disrupts overall health of the tree.

Currently there are very few guidelines aiding the design of a container for trees. Besides the consideration for water flow, the integrity of the container is one aspect of the design that is critical. The structural integrity of the container which include the type of

* Corresponding author.
E-mail addresses: chrahardjo@ntu.edu.sg (H. Rahardjo), namalia@ntu.edu.sg (N. Amalia), Rjdwee@gmail.com (J.D. Wee), cecleong@ntu.edu.sg (E.C. Leong), genevieve_ow@nparks.gov.sg (L.F. Ow), akitpy@nus.edu.sg (P.Y. Tan).
[1] Website: http://www.ntu.edu.sg/cee/staff/infrastructure/academic/chrahardjo.asp.

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material, the thickness and the size of the container as well as the maximum extent of perforations have to be accounted for. The maximum amount of perforations has a key role underpinning the integrity of the container especially during transportation. Therefore, the amount of perforations is more likely controlled by the integrity of the container. In that aspect, the water flow characteristics through the perforations will generally be affected by the soil properties.

Soil used for planting in Singapore adhered to the guidelines derived from National Parks Board, the governmental custodian for trees and greenery in the country (NParks, 2011). The top soil generally called ASM (approved soil mixture) is a mixture of sand, residual (in-situ soil) and organic matter. Still, it is noteworthy that the used top soil varies greatly (Indrawan, Rahardjo, & Leong, 2006; Rahardjo et al., 2014). The variation in the ASM used for tree planting in the container as well as the soil surrounding the container will affect the infiltration of water across the container. Therefore, while the idea of containerised trees does seem to be ideally suited for an urban environment, it is still critical that studies are carried out to better understand the effect of soil hydraulic properties between the soils inside and outside of the container.

Therefore, in this study, a specialized container was designed and built. The container was filled with top soil and a tree was planted in the container creating a containerized (enclosed) system. The containerized system was planted by the side of a carriageway. The soils inside and outside of the container were monitored using various sensors. In order to study the effect of hydraulic properties of the soil, the flow of water in this enclosed system, as well as a parametric study using seepage finite element models were carried out. In turn, the model was verified with field measured data.

2. Theoretical consideration

Water flow in the container is a case of water flow in an unsaturated porous medium. The water flow in unsaturated soil follows the law of water flow in saturated soil which is Darcy's Law. In a two-dimensional field, the water flow could be described by Richards' (1931) equation as follows:

$$m_w^2\gamma_w\frac{\partial h_w}{\partial_t} = \frac{\partial}{\partial x}\left(-k_{wx}\frac{\partial h_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(-k_{wy}\frac{\partial h_w}{\partial y}\right) + q \tag{1}$$

Where m_w^2= slope of soil-water characteristic curve; γ_w = unit weight of water; h_w = hydraulic head or total head; t = time; k_{wx} = coefficient of permeability with respect to water as a function of matric suction in the x-direction; k_{wy} = coefficient of permeability with respect to water as a function of matric suction in the y-direction; and q = applied flux at the boundary.

The relationship between the coefficient of permeability and water content is commonly described as a permeability function. The permeability function can be obtained by a direct measurement or indirect measurement. Direct measurement of permeability in the laboratory is a time-consuming process, particularly when the soil has reached low water content. Therefore, indirect measurements of permeability are commonly conducted. One of the popular prediction methods of permeability functions was proposed by Childs and Collis-George (1950) where the permeability function is predicted from soil-water characteristic curves (SWCC). SWCC is the relationship between water content or degree of saturation and matric suction. The theory and procedure of this method can be found in Fredlund and Rahardjo (1993).

3. Material and methods

3.1. Site instrumentation, container and soil properties

A containerized tree system was planted in the ground in the eastern part of the island of Singapore. The container was 1.8 m in diameter and 1.5 m in height. There were perforations that occupied 25% of the wall of each container to allow water to flow in and out of the container. The extent of these perforations was calculated based on the structural integrity requirements of the container. The container is shown in Fig. 1. Small tip tensiometers (Type 2100F, Soilmoisture Corp) were used to monitor the development of pore-water pressures inside and outside the container. There were four tensiometers installed, two inside and two outside the container, at depths of 0.4 m and 1.2 m. The tensiometers were connected to pressure transducers and a data logger system (CR1000, Campbell Scientific Ltd) for automated data collection and measurement. The whole system was powered using a solar panel reinforced with batteries. The diagram of the instrumentation is shown in Fig. 2.

Fig. 1. Container with perforation on the wall.

The soil mix inside the container was sampled for testing and data from other experimental sites where soils were found to be similar to the soil outside the container (Rahardjo, Satyanaga, Leong, & Wang, 2013) were assessed. The results of the basic properties along with the test standards used during investigation are presented in Table 1. The SWCCs of the soils inside and outside the container are shown in Fig. 3. The corresponding permeability functions predicted from the SWCCs are presented in Fig. 4. The soil mix inside the container had a lower density and a higher permeability than the soil outside the container. The soil mix inside the container also had lower saturated volumetric water content but higher air entry value compared to the soil outside the container.

3.2. Verification of numerical model

The focus of this study was to investigate the effect of different soil hydraulic properties on the water flow behaviour around a container using a parametric numerical study. The site instrumentation data were used to verify the results derived from the numerical model. The results of the numerical model were compared with the instrumentation data within a specified period when there was rainfall. The numerical model (Fig. 5) was generated using SEEP/W (Geo-slope international Ltd, 2012) (Table 2).

The model was axisymmetric and the width of the model was 6.0 m and the height of the model was 6.5 m. The boundary condition of the model at the bottom was head equals to 4.3 m (the groundwater table was located at 2.2 m below ground level). The boundary condition on the side of the model above the ground water table was no flow condition. The boundary condition at the surface was a unit flux equal to the rainfall intensity (data obtained from the nearest weather station at the experimental site). For the verification of the numerical model, data from 25 December 2010 was used. An evaporation of 6 mm/d was