UNIVERSITI PUTRA MALAYSIA

MODELING INFILTRATION CAPACITY OF PERMEABLE CHANNELS UNDER STATIC AND DYNAMIC HYDRAULIC CONDITIONS

AHMED MOHAMMED SAMI AL-JANABI

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By

AHMED MOHAMMED SAMI AL-JANABI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

July 2018

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DEDICATION

To

My parents

My parents-in-law

My lovely family, wife and children

&

Everybody who support my journey to obtain

Degree of Doctor of Philosophy

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

MODELING INFILTRATION CAPACITY OF PERMEABLE CHANNELS UNDER STATIC AND DYNAMIC HYDRAULIC CONDITIONS

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July 2018

Chairman : Associate Professor Abdul Halim Bin Ghazali, PhD
Faculty : Engineering

Increasing infiltration rate of stormwater is important for improving the control of stormwater quantity to foster sustainable urban stormwater management. In the design of stormwater channels, the effect of infiltration on the channel flow and the effects of hydraulic parameters such as water level, channel cross section, flow velocity, and vegetation, on the infiltration capacity of channels are usually ignored. The present study aimed to examine the effects of hydraulic parameters on the infiltration capacity of permeable channels through laboratory investigation on channel models under static and dynamic hydraulic conditions. The study also aimed to develop empirical models for the variations of infiltration capacity with flow hydraulic parameters, in order to improve the design of permeable stormwater channels. Different channel models were constructed for each of the above condition, and different sets of hydraulic and channel boundary conditions were used to characterise the channel flow considering the effect of infiltration and to develop empirical models for predicting infiltration capacity for permeable channels. The effect of channel cross section on the flow reduction by seepage and infiltration processes were first examined under static or standing water condition, with various initial water levels, channel base widths and side slopes. Regression analysis was used to develop an equation for predicting the rate of unsteady seepage over time, and the equation was used to examine several cases of different flow cross-sectional areas and channel dimensions, and subsequently, to determine the section that produced highest infiltration and seepage under the unsaturated soil condition. Moreover, five existing infiltration models, namely, the Kostiakov, Horton, Modified Kostiakov, Philip, and Soil Conservation Service (SCS) models were evaluated, and then they were modified by incorporating the cross-sectional flow area parameters (depth y, side slope m, and bottom width b) into them. Under the dynamic or flowing water condition, the mass-balance method was used for the estimation of infiltration rate, and the experimental tests employed five inflow rates (Q_{in} = 5.5, 7.5, 9.5, 11.5, 13.5 l/s), with three downstream check dam heights (h_w = 10, 15, 20 cm). In addition, two other sets of experiments were conducted to investigate the effects of grass cover and subsurface water on infiltration rate. The findings were used to quantify and compare the different cases in terms of the infiltration rate and cumulative infiltration, and then to develop predictive equations that include the effect of hydraulic parameters for estimating the infiltration rate in permeable channels. The results indicated that the infiltration and seepage rates increase with increasing initial water level irrespective of the base width and side slope. Moreover, an increase in the side slope increases both the infiltration and seepage rates, with the effect becoming more significant as the initial water level increases, while the effect of varying the base width is insignificant. It has also been found that increasing the wetted perimeter or top width of a channel enhances the infiltration rate if this is achieved by varying the side slope, and not by increasing the base width. In the evaluation of the five infiltration models, a comparison using the coefficients of determination R^2 obtained before and after the parameters were added into the models reveals that the difference between the observed and predicted values using the modified models was significantly reduced, and R^2 increased sharply from 0.14, 0.158, 0.164, 0.146 and 0.162 for the Kostiakov, Horton, Modified Kostiakov, Philip, and SCS models, respectively, to 0.732, 0.621, 0.735, 0.718 and 0.609. Two predictive equations were developed finally using the nonlinear regression analysis after introducing the four hydraulic parameters (y, m, b and v) into the Kostiakov and Modified Kostiakov models, which were chosen to be improved because they have been shown to give better performance than the other models during the previous analysis. The latter model with the new parameters was used for the analysis of a channel section to determine the best conditions to obtain the highest infiltration rates for given flow rates and then to plot graphs of the variation of cumulative infiltration F over time for a grassed channel with different check dam heights and inflow rates. Cumulative infiltration quantity after 90 min for two cases of channels, with and without check dams, were compared and the results reveal that the percentage of total infiltrated water volume increased from 8% to 14% when using check dams with 20-cm height and 10-m spacing compared to the channel without the check dams. Modeling the variations of infiltration capacity with hydraulic parameters in permeable channels using the models developed in this study therefore promises better stormwater management and provides a valuable decision support tool for designing the permeable channels.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMODELAN KEUPAYAAN PENYUSUPAN SALURAN TELAP DI DALAM KEADAAN HIDRAULIK STATIK DAN DINAMIK

Oleh

AHMED MOHAMMED SAMI AL-JANABI

Julai 2018

Pengerusi : Profesor Madya Abdul Halim Bin Ghazali, PhD
Fakulti : Kejuruteraan

Meningkatkan kadar penyusupan air larian hujan adalah penting untuk menambah baik kawalan kuantiti air larian hujan bagi memupuk pengurusan air larian hujan bandar yang lestari. Dalam mereka bentuk saluran air hujan, kesan penyusupan ke atas aliran saluran dan kesan parameter hidraulik, iaitu paras air, keratan rentas saluran, halaju aliran dan tumbuh-tumbuhan dalam saluran, ke atas keupayaan penyusupan biasanya diabaikan. Kajian ini bertujuan untuk menilai kesan parameter hidraulik ke atas kapasiti penyusupan saluran telap melalui penyiasatan makmal ke atas model saluran di dalam keadaan hidraulik statik dan dinamik. Kajian ini juga bertujuan untuk membangunkan model empirikal untuk meramalkan variasi kapasiti penyusupan dengan parameter hidraulik, bagi meningkatkan reka bentuk saluran air hujan yang telap. Model saluran yang berlainan dibina bagi setiap keadaan di atas, dan keadaan hidraulik dan sempadan saluran yang berlainan digunakan untuk mencirikan aliran dalam saluran dengan mengambil kira kesan penyusupan serta untuk membangunkan model empirikal bagi menjangka keupayaan penyusupan bagi saluran telap. Kesan keratan rentas saluran ke atas pengurangan aliran melalui proses resapan dan penyusupan mula-mula dikaji di dalam keadaan statik atau air bertakung, dengan pelbagai aras air awal, lebar dasar saluran dan cerun sisi. Analisis regresi digunakan untuk membina satu persamaan bagi meramalkan kadar resapan tak mantap melawan masa, dan persamaan itu digunakan untuk meneliti beberapa kes saluran dengan luas keratan-rentas aliran dan dimensi saluran yang berbeza, dan seterusnya menentukan keratan yang menghasilkan kadar penyusupan dan resapan tertinggi di dalam keadaan tanah tak tepu. Selain itu, lima model penyusupan sedia ada, iaitu model Kostiakov, Horton, Modified Kostiakov, Philip, dan Soil Conservation Service (SCS) telah dinilai, dan kemudian model tersebut telah diubahsuai dengan memasukkan parameter luas aliran keratan rentas (kedalaman y, cerun sisi m, dan lebar dasar b) ke dalamnya. Di dalam keadaan dinamik atau air mengalir, kaedah imbangan-jisim telah digunakan untuk menganggarkan kadar penyusupan, dan ujian telah dilakukan menggunakan lima kadar aliran masuk (Q_{masuk} = 5.5, 7.5, 9.5, 11.5, 13.5 l/s), dengan tiga ketinggian empangan penyekat hiliran (h_w = 10, 15, dan 20 cm). Di samping itu, dua set eksperimen lain telah dijalankan untuk menyiasat kesan kewujudan rumput dan air bawah permukaan ke atas kadar penyusupan. Hasil yang diperolehi digunakan untuk mengira dan membandingkan saluran telap yang berlainan, dari segi kadar penyusupan dan penyusupan kumulatif, dan kemudian untuk membangunkan persamaan ramalan yang merangkumi kesan parameter hidraulik untuk menganggarkan kadar penyusupan di dalam saluran telap. Keputusan menunjukkan bahawa kadar penyusupan dan kadar resapan meningkat dengan peningkatan aras air awal tanpa mengira lebar dasar dan cerun sisi. Selain itu, peningkatan cerun sisi meningkatkan kedua-dua kadar penyusupan dan resapan, dengan kesannya menjadi lebih signifikan apabila aras air awal meningkat, manakala kesan perbezaan lebar dasar adalah tidak signifikan. Didapati juga bahawa peningkatan perimeter basah atau lebar atas saluran dapat meningkatkan kadar resapan sekiranya ia dicapai dengan mengubah cerun sisi, dan bukan dengan menambahkan lebar dasar. Di dalam penilaian lima model penyusupan, perbandingan menggunakan koefisien penentuan R^2 yang diambil sebelum dan selepas parameter ditambah ke dalam model itu menunjukkan bahawa perbezaan di antara nilai yang dicerapkan dan nilai yang diramalkan menggunakan model yang diubahsuai telah dikurangkan dengan ketara, dan R^2 meningkat dengan mendadak daripada 0.14, 0.158, 0.164, 0.146 dan 0.162 masing-masing bagi model Kostiakov, Horton, Modified Kostiakov, Philip, dan SCS, kepada 0.732, 0.621, 0.735, 0.718 dan 0.609. Akhir sekali, dua persamaan ramalan telah dibangunkan menggunakan analisis regresi tak linear dengan memperkenalkan empat parameter hidraulik (y, m, b dan v) ke dalam model Kostiakov dan Modified Kostiakov. Dua model ini telah dipilih untuk diperbaiki kerana kedua-dua model itu telah menunjukkan prestasi yang lebih baik daripada model lain semasa analisis terdahulu. Model kedua dengan parameter baru digunakan untuk menganalisis satu seksyen saluran untuk menentukan keadaan terbaik untuk memperolehi kadar penyusupan tertinggi bagi kadar aliran tertentu dan kemudian memplot graf variasi penyusupan kumulatif F dengan masa untuk saluran berumput dengan ketinggian empangan sekatan dan kadar aliran masuk yang berbeza. Kuantiti penyusupan kumulatif selepas 90 minit untuk dua kes saluran, dengan dan tanpa empangan sekatan, telah dibandingkan dan hasilnya menunjukkan bahawa peratusan jumlah isi padu air penyusupan meningkat daripada 8% ke 14% apabila menggunakan empangan sekatan dengan ketinggian 20-cm dan jarak 10-m berbanding saluran tanpa empangan sekatan. Oleh itu, pemodelan variasi kapasiti penyusupan dengan parameter hidraulik dalam saluran telap menggunakan model yang dibangunkan di dalam kajian ini menjanjikan pengurusan air larian hujan yang lebih baik dan mengemukakan suatu alat sokongan keputusan yang berharga dalam mereka bentuk saluran telap.

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I certify that a Thesis Examination Committee has met on 20 July 2018 to conduct the final examination of Ahmed Mohammed Sami Al-Janabi on his thesis entitled "Modeling Infiltration Capacity of Permeable Channels under Static and Dynamic Hydraulic Conditions" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Farah Nora Aznieta binti Abdul Aziz, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Md. Rowshon Kamal, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Aimrun Wayayok, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Aminuddin Ab. Ghani, PhD
Professor
Universiti Sains Malaysia
Malaysia
(External Examiner)

RUSLI HAJI ABDULLAH, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 27 September 2018

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Abdul Halim Ghazali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Badronnisa Binti Yusuf, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Thamer Ahmad Mohammad Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
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- the research conducted and the writing of this thesis was under our supervision;
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Name of Chairman of Supervisory Committee: Associate Professor Dr. Abdul Halim Ghazali

Signature: ______________________
Name of Member of Supervisory Committee: Dr. Badronnisa Binti Yusuf

Signature: ______________________
Name of Member of Supervisory Committee: Professor Dr. Thamer Ahmad Mohammad Ali

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α	Dimensionless parameter in Figure 2.2
α	Coefficient representing the rate of reduction in hydraulic conductivity k or water content θ as the pressure head ψ becomes more negative, (Equation (2.16))
A	Channel cross-sectional area (L^2)
A_d	Drainage area (L^2)
A_{md}	Cross-sectional area at mid-point of channel length (L^2)
A_1 and A_2	Channel cross-sectional area at different sections (L^2)
$\frac{\Delta A}{\Delta t}$	The decrease of the cross-sectional flow area with respect to time (L^2/t).
b	Channel base width (L)
C	Runoff coefficient, (Equation (2.19))
C	Constant = 1,300 (sec^2/ft^2), (Equation (2.25))
C_a	Constant rate of infiltration (L/t), for Equation (2.30)
C_a and C_b	Constants for Equation (4.1)
C_n	Dimensionless retardance factor depending on the type and the maturity of the grass as shown in Table 2.1
C_1, C_2 C_3, C_4 and C_5	Constants for Equation (4.2)
C_1, C_2 C_3 and C_4	Constant of hydraulic parametes for Equations (4.11) and (4.13)
CSV	Cumulative seepage volume per unit length (L^3)
d_q	Depth of flow at Q_q (L)
D	Hydraulic depth (L), D = A/T
f	Infiltration rate (L/t)
f_0	Initial infiltration capacity (L/t)

f_c	Final infiltration capacity (L/t)
f_p	Infiltration capacity (L/t)
F	Cumulative infiltration (L/t)
F_{hp}	Function of hydraulic parameters
F_r	Frode number (dimensionless)
F_s	Seepage function (dimensionless), for Equation (2.17)
g	Gravitational acceleration (L/t^2)
h_1 and h_2	The heights above a reference level of water in a manometer terminated above and below the soil layer respectively, in Dracy's Law (Equation (2.14))
h_w	Downstream check dam heights (L)
HRT	Hydraulic residence time (t)
I	Rainfall intensity (L/t)
k	Constant representing the rate of decrease in f_p (Equation (2.28))
k	Soil permeability
k_u	Unsaturated hydraulic conductivity
k_s	Saturated hydraulic conductivity
K	Function of the side slope m, which decreases with increasing side slope (Table 2.2).
K_k, and α	Empirical constants (non-dimensional) for Kostiakov, modified Kostiakov and SCS models (Equations (2.27), (2.29)and (2.31))
K_v	Unit conversion factor For Equation (2.12), $K_v = 3.28\ m^{-1}=1.0\ ft^{-1}$
L_d	Thickness of the soil in Dracy's Law (Equation (2.14))
L	Length of the channel (L)
m	Channel side slope (H:V)
n	Manning's roughness coefficient
P	Channel wetted perimeter (L)

$\bar{P}$	The average wetted parameter (L), $\bar{P} = (P_1 + P_2) / 2$
P_1 and P_2	The wetted parameter P values at the beginning and end of a time interval respectively
q	Darcy's water flow which is the volume of water crossing a unite area in unit time
q_L	Lateral inflow or outflow
q_s	Seepage discharge per unit length of a channel (L^2/t.L)
Q	Flow rate (discharge)
Q_f	Peak infiltration flow rate (L^3/t)
Q_{in}	Inflow rate directed to a channel (L^3/t)
Q_{out}	Outflow rate from a channel (L^3/t)
Q_p	Peak runoff rate (L^3/t)
Q_q	Discharge at water quality flow (L^3/t)
R	Hydraulic radius (L) = A/P
R^2	Coefficient of determination
S	Sorptivity of the soil ($Lt^{-1/2}$)
S_0	Longitudinal channel bottom slope (L/L).
$\frac{\Delta S}{\Delta t}$	Change in channel storage over the time intervals (L^3/t).
SCS	Soil Conservation Service infiltration model
t	Time
t_p	Time to peak flow
t_d	Time to downstream
T	Channel top width (L)
v	Mean velocity (L/t)
V	Cross-sectional average velocity (L/t)
V_m	Volume of water

V_q	velocity at Q_q (L/t)
V_1 and V_2	Mean velocity at different channel sections (L/t)
x	Displacement in the main flow direction (L)
y	Water depth (L)
y_c	Critical flow depth (L)
y_n	Normal flow depth (L)
y_p	Flow depth at peak flow (L)
z	Elevation head (L)
θ	Soil volumetric water content
θ_r	Residual volumetric water content
θ_s	Saturated volumetric water content
ρ	Water density
ψ	Pore-water pressure head

CHAPTER 1

INTRODUCTION

1.1 Background

Modern urban development typically creates impervious areas, which reduce the infiltration of rainwater and increase the volume of runoff. When combined with urbanization, climate change influences the hydrologic variables in urban areas, thereby increasing the frequency and magnitude of urban flooding, and negatively impacting both humans and the environment (Zhou, 2014).

The philosophy of urban stormwater management has therefore shifted away from narrow traditional approaches, i.e., 'rapid discharge' or 'collecting and conveying stormwater away from urban areas as quickly as possible', to new sustainable approaches that leverage more natural methods (Villarreal, 2005). For example, source control uses storage and infiltration methods that allow rainfall events to be conveyed and infiltrated along the surface rather than in underground pipes (Miguez et al., 2012). Reducing the volume of runoff by infiltration through permeable surfaces at the source lessens the effort needed to control the remaining runoff at the downstream basin (Ferguson, 1994). Moreover, sustainable approaches consider other important aspects in urban water management, such as reducing the volume of runoff, water quality, recreational value, protection of the environment, and multiple water uses (Zhou, 2014).

Perceiving these environmental and economic benefits therefore have resulted in the growing interest in infiltration to be a sustainable alternative approach or at least with conjunction with the conventional drainage practices. Several different terms are used to describe these new approaches in different parts of the world, albeit with minor differences in concept and practice. Some well-known terms include low impact development (LID), sustainable urban drainage systems (SUDS), water sensitive urban design (WSUD), and best management practices (BMPs). Numerous studies of the differences and applications of these approaches have been conducted (e.g., Fletcher et al., 2014; Zhou, 2014; Miguez et al., 2012; Shutes and Raggatt, 2010).

Permeable channels are commonly used for sustainable urban drainage and management of stormwater quantity. The term "Permeable channels" may refer to unlined earthen channels, or channels with flexible lining which may consist of grass, rip-rap, or gabions (DSD, 2013), as shown in Figure 1.1. Lining should be provided to channel bottom and side slopes when flow velocity exceeds 1 to 2 m/s (Chow, 1959), and hence unlined earthen channels are not preferred for stormwater practices because of the concern of soil erosion at high flow velocity.

The use of grass, where practical, is the most preferred lining type for stormwater channels, because of the low cost of grass lining that is much less than other lining types, in addition to grass ability to stabilize the channel bed and sides, prevent soil erosion, consolidate the soil mass, and provide water quality benefits (CCSMDM, 2014). However, some conditions may prevent the use of grass lining such as the high flow velocities, standing water or continuous flowing, excessive shade, lack of maintenance and inadequate topsoil (CCSMDM, 2014).

a) Rip-Rap channel **b) Gabions channel**

c) Grassed channel

Figure 1.1 : Types of permeable channels used for stormwater management

Permeable stormwater channels can be categorized under the slow transport group of sustainable urban drainage (Figure 1.2) as they link several on-site control systems, delay rapid runoff, and reduce the volume of runoff by their infiltration function (Stahre, 2008). Permeable channels are also used to enhance the quality of stormwater through infiltration, sedimentation, and filtration (Boogaard et al., 2014).

Infiltration capacity of permeable channels may be influenced by many factors that may make the infiltration rate through permeable channel differ from other infiltration devices. Therefore, the ability to accurately quantify infiltration rates is very important in the design of permeable stormwater channels, because it enables the capability of the channels to be assessed to determine if they can perform the required functions.

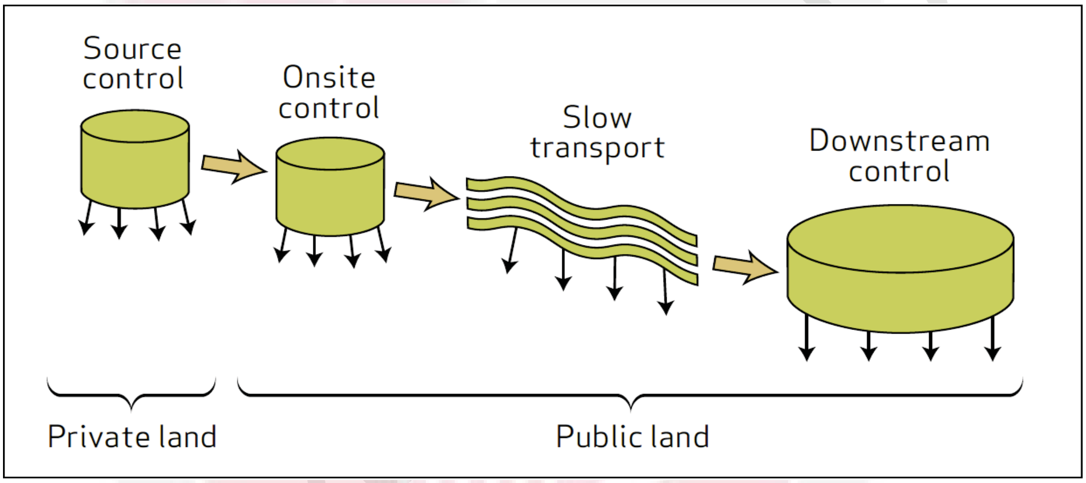

Figure 1.2 : The Four Groups of Sustainable Urban Drainage (Stahre, 2008)

1.2 Problem Statement

The use of permeable stormwater channels introduces the concern about the effects of infiltration on the hydraulics behavior of flow in such channels, as well as the effect of hydraulics parameters such as water level, base width, side slope, velocity, and vegetation, on infiltration rate. However, design methods in most cases, are simplified and based on experience and empirical design criteria gained from existing stormwater channels (Grinden, 2014).

Manning's equation is usually used in the design of a channel cross section at a required discharge, and then the design is usually checked either versus the maximum allowable velocity for erosion protection and for water quality (e.g. DID, 2012; DPLG, 2010) or versus the minimum allowable hydraulic residence time for water quality design (e.g. Caltrans, 2012; WEF, 2012). However, even when the infiltration rate is taken into consideration, the variation of infiltration rate with several factors such as the water depth, flow velocity and channel cross section as well as the variation of infiltration capacity with time are usually ignored (e.g. St. Johns River, 2010; Wanielista and Yousef, 1993).

Disregarding the infiltration effect on flow in design procedures of permeable stormwater channels often results in overdesign them for a given flow rate and channels become bigger than required (Grinden, 2014).

Thus, it is essential to investigate the factors affecting the infiltration process through the beds and sides of permeable channels and then to relate the infiltration rate with the channel flow to improve the design of permeable stormwater channels as an infiltration device.

1.3 Research Objectives

The study aims to investigate factors affecting infiltration process and flow reduction in permeable open channels under static and dynamic hydraulic conditions, and subsequently to develop empirical models for the variations of infiltration capacity with flow hydraulic parameters, in order to improve the design of permeable stormwater channels.

The specific objectives of the study are:

1. To examine the effect of the channel cross section on seepage and infiltration rates in permeable channels under static condition.
2. To evaluate the performance of five existing infiltration models for estimating the infiltration rate in permeable open channels under static condition.
3. To examine the effect of flow hydraulic parameters on infiltration capacity of permeable stormwater channels under dynamic condition.
4. To develop empirical models for predicting the infiltration capacity for permeable stormwater channels with considering various channel flow characteristics.

1.4 Significance of the Study

This study provides more insight on the effect of the hydraulic parameters on the flow with infiltration in permeable channels. To improve the efficiency of a permeable stormwater channel, the channel section that, within the design criteria, maximizes infiltration and seepage through the channel bed and side slope should be chosen. A good understanding of how infiltration rates are affected by flow hydraulic conditions helps to choose the optimal channel cross section and height of check dams that allow the maximum possible infiltration rate. Although some studies show how the infiltration rate is affected by the ponding depth of the water and surface slope, they were limited to overland flow and the effect of the channel cross section on the infiltration rate has largely been ignored. While the ponding depth and slope may not be significant infiltration factors in some hydrologic models, the water level and side slope in a channel may prove important when seeking to maximize the infiltration rate in a particular channel with a given flow rate. Modeling the variations of infiltration rate with flow hydraulic parameters in permeable channels promises best stormwater management and provide a valuable decision support tool in designing permeable channels. Moreover, the application of the findings of this study to the design of a stormwater channel promises to reduce the length of the channel and occupied land, thereby decrease the construction and maintenance costs.

1.5 Scope and Limitations

The scope of this research is to investigate experimentally the effects of flow hydraulics parameters, which are water level, base width, side slope, and velocity on infiltration rate in a permeable channel and their effectiveness in flow reduction.

For better understanding the characteristics of flow with infiltration in permeable open channels, flow hydraulics parameters were studied using different sets of hydraulic and soil conditions, and the study involved the determination of infiltration rate through permeable channels in two flow conditions, namely, static and dynamic, and hence different physical channel models were developed in the laboratory for each condition.

Under the static condition, the ponding method was used for the infiltration and seepage tests under unsaturated soil conditions. Physical channel models were used to investigate the effects of the channel section on the infiltration and seepage rates in a permeable channel, and determine the section that maximizes water reduction by infiltration and seepage under the unsaturated soil condition. The experimental tests includes four initial water depths (y = 0.15, 0.25, 0.35, and 0.45 m), three base widths (b = 1, 0.5, and 0.2 m), and three side slopes (m = 2, 3, and 4). The physical channel models were also used to evaluate the performance of five infiltration models, namely, the Kostiakov, Horton, Modified Kostiakov, Philip, and Soil Conservation Service (SCS), for estimating the infiltration rate in permeable stormwater channels versus the measured values.

Under the dynamic condition, the mass-balance method was used for infiltration rate estimation, and the experimental tests includes five inflow rates (Q_{in} = 0.0055, 0.0075, 0.0095, 0.0115, 0.0135 m^3/s), with three downstream check dam heights (h_w = 10, 15, and 20 cm). In addition, two other sets of experiments were conducted to investigate the effects of grass cover and subsurface water on infiltration rate. The results were used to quantify and compare the different cases in terms of the infiltration rate and cumulative infiltration for better surface water reduction. All comparisons focused on the hydraulic considerations of channel design rather than economic analysis of different alternatives.

There are many factors that may influence the infiltration capacity of permeable channels, however, it is difficult to consider all these factors. In this study, the flow hydraulics parameters which are the water level, channel section, and flow velocity were taken into account in the investigation, while the other factors were considered as fixed parameters.

Soil used to form the permeable layer in the test channels was natural soil collected from the farm of the Universiti Putra Malaysia, which was homogeneous and isotropic, and represented only one type of soil. Hence, the analysis and development of predictive equations throughout this study are applicable for this type of soil, and further investigations should be conducted to confirm their suitability for other types. Moreover, only one texture of top-soil and one type of grass, which known as Cow grass, were used for the channel under the dynamic phase of the study.

The rate of seepage through the natural unsaturated soil is significantly influenced by the infiltration rate from the surface to the top soil when water stands, that is the water is not flowing in a channel. Therefore, seepage was studied under the static condition only, while it was considered insignificant and thus ignored under the dynamic condition.

The model scales were limited according to the space available for the permeable channel fabrication in the hydraulic laboratory at the Faculty of Engineering, Universiti Putra Malaysia. Experiments were limited to the laboratory temperature, and the filed capacity of soil saturation.

Channel model for dynamic condition was placed inside an existed concrete flume which has a length of 16 m after the flow inlet, width of 1.5 m and height of 1.2 m. The reason of placing the model inside the concrete flume was to use its facilities such as pumping and draining water, measuring inflow and outflow, supporting water level measurement tools, and placing the movable current meter.

The study considered only one longitudinal slope of a channel, and did not cover the effect of longitudinal slope variations on infiltration capacity of channels. Moreover, initial water level of flow was reached very fast comparing to the case of rainfall on permeable stormwater channels, and water for dynamic condition was re-circulated during the experiment by collecting both conveyed and infiltrated water at the end of channel and pumping it to the overhead tank and re-circulating again.

The analysis throughout the study was based on statistical approach using IBM SPSS Statistics software (version 21). Moreover, SPSS software was used for developing predictive equations and fitting their parameters because of that the mathematical basis of all available software does not consider the variations of infiltration rate with the hydraulic parameters in stormwater channels. While numerical analysis is highly relevant in this work, it was not used due to time limitation.

1.6 Thesis Layout

This thesis is composed of five chapters. Chapter One presents an overview of the use of permeable channels for sustainable stormwater management and their functions, the problems accompanying such channels, and the objectives of the study, together with the significance, scope and limitations of the current research.

Relevant literature is reviewed in Chapter Two. This Chapter reviews the characteristics of flow in open channels and the variables governing the flow in permeable stormwater channels. The Chapter also reviews extensively the previous studies on the effect of channel cross section on seepage and infiltration rates in different conditions and practices. Moreover, this Chapter reviews the design procedures of permeable stormwater channels, the methods for estimating infiltration rate through permeable channels, and summarises the formulas of five infiltration models, namely, the Kostiakov, Horton, Modified Kostiakov, Philip, and Soil Conservation Service (SCS). Finally, a summary of the literature review and the research gaps related to flow with infiltration in a permeable channel is presented in this chapter.

Experimental setup, channel material, experimental method, and data collection for the two hydraulic conditions, namely, static and dynamic conditions, are described in the third Chapter. Moreover, Chapter Three also comprises a description of the two separate laboratory pre-tests that conducted to examine how the placement of soil on an open to the atmosphere boundary condition may affect the infiltration and seepage rates, and how the results would differ if the experiments were performed in a native channel.

Chapter Four presents the results of the experiments from the two phases. Discussion in Chapter Four was based on the comparisons among different cases and their effect on the flow with infiltration in permeable channels under static and dynamic hydraulic conditions using graphs, tables and empirical equations. An example of modelling flow with infiltration with two cases in a grassed channel was detailed at the end of Chapter Four.

Finally, Chapter Five presents a summary and conclusions of the study, as well as suggestions for some future studies.

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