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Validation of Manning's *n* equations for a swale with a subdrainage channel as water storage[1]

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Abstract

Introduction: Stormwater management is the effort to reduce runoff of rainwater ormelted snow into streets, lawns and other sites and the improvement ofwater quality, according to the United States Environmental Protection Agency (EPA). When stormwater is absorbed into the soil, it is filtered andultimately replenishes aquifers or flows into streams and rivers. However, when heavy rainwater hits, ground saturated by water createsexcess moisture that runs across the surface and into storm sewers androad ditches. This water often carries debris, chemicals, bacteria, eroded soil, and other pollutants, and carries them into streams, rivers, lakes, or wetlands. In urban and developed areas, impervious surfaces such as pavement androofs prevent precipitation from naturally soaking into the ground. Instead, water runs rapidly into storm drains, sewer systems anddrainage ditches and can cause flooding, erosion, turbidity (ormuddiness), storm and sanitary sewer system overflow, andinfrastructure damage. However, stormwater design and "greeninfrastructure" capture and reuse stormwater to maintain or restorenatural hydrologies. Detaining stormwater and removing pollutants is the primary purpose ofstormwater management. Pervious Surfaces that are porous and allowrainfall and snowmelt to soak into the soil, Gray infrastructure, suchas culverts, gutters, storm sewers, conventional piped drainage, andBlue/Green infrastructure that protect, restore, or mimic

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the naturalwater cycle, all play a part in stormwater management.

In stormwater management systems, a swale is one of the flow control-at-source facilities. The application of swale with a subdrainage channel in Malaysia urban areas is new and promising to control urban flash floods. Rainfall-runoff infiltrate to the subdrainage can be stored and become proper irrigation sources and increase the benefits of water productivity due to maximize the income and profits either in agricultural yield or as non-portable water supply.

Material and methods: The Manning Equation is the most commonly used equation to analyze open channel flows. It is a semi-empirical equation for simulating water flows in channels and culverts where the water is open to the atmosphere, i.e. not flowing under pressure, and was first presented in 1889 by Robert Manning. The channel can be any shape - circular, rectangular, triangular, etc. The units in the Manning equation appear to be inconsistent. The Manning Equation was developed for uniform steady state flow. For uniform steady flows, the energy gradeline = the slope of the water surface = the slope of the bottom of the channel. Manning n varies with the roughness of the pipe, culvert, or channel. The higher the n, the rougher the material. This study was done in REDAC's Hydraulic Laboratory, Engineering Campus, Universiti Sains Malaysia, and the data have been used to validate the suggested Manning equations. By using flow meter and measuring tape, velocity and flow depth of each case (GFO, GPO2 and GPO4) with different slopes at M2, M3 and M4 were recorded. The measurements of the velocity and flow depth have been taken three times at each location. Data recorded have been use as input to calculate flow. All data were analysed by using Microsoft Excel 2013.

Results: Observed flow rates gained in this study, were used to validate Manning's (n) equation that developed through the previous study that recommended to be used in designing subdrainage channel. The performance of flow capacity in a single module of the swale subdrainage channel is also discussed. An experimental setup was carried out in a six-meter flume by using the River Engineering and Urban Drainage Research Centre (REDAC) module as a subdrainage channel or ecological subsurface module. These physical model test runs were conducted to evaluate the efficiency of hydraulic capacity due to backwater or blockage effects at the end of the channel. Three gate scenarios were applied to represent the blockage. Manning roughness coefficient influenced inversely proportionate by flow capacity with maximum value is 0.020. It shown in the subdrainage module, the main parameter that controls the flow attenuation is module roughness itself.

Conclusion: Flash flood issues in the urban area become tremendously crucial and flow attenuation is believed may tackle the issue. By slowing down the flow to the downstream area, a high infiltration rate would have occurred and implementation of a subdrainage channel with a single module that is located underneath the swales can accelerate the infiltration process consequently slow down the upstream flow to reach the downstream area. It is concluded that the developed equation for Manning's prediction has been validated through a good and significant agreement between predicted and observed results with an R^2 value of 0.77.

Keywords: Ecological Subsurface Module, Hydraulic Performance, Manning's Roughness Coefficient, Runoff, Subdrainage, Swale, Water Productivity.

1. Introduction

Population growth in developing countries especially in urban areas may lead to rapid urbanization. Urbanization is one of many causes that contribute to land use changing, typically from pervious to impervious surface. This scenario consequently affects the hydrological cycle in that area by decreasing rainwater interception by trees, reducing infiltration of surface runoff into the ground, and consequently increasing the amount of surface runoff (Zhang *et al*., 2021; Xu *et al*., 2021; Ekka *et al*., 2021). It may lead to massive stormwater problems mainly during high-intensity rainfall for instance flash floods and water pollution, especially in the area that is already densely built. Thus, surface runoff is crucial to consider and to control (Davidsen *et al*., 2018) to avoid overflow of concrete drain and consequently may cause flash flood in the downstream area.

To avoid these issues especially in a tropical region where receives high-intensity rainfall regularly (Julien *et al*., 2010), sustainable applications of stormwater management must be properly included in the planning for a new development. Kemper & Schlenkhoff (2019) suggested new sustainable design approaches in urban drainage engineering are required to manage urban flooding. Difference regions and countries have different terminology of sustainable urban stormwater management practice such as Sustainable Urban Drainage System (SUDS), Low Impact Development (LID), Water Sensitive Urban Design (WSUD), Best Management Practices (BMPs), Sustainable Urban Water Management (SUWM), Green infrastructure, etc (Fletcher *et al*., 2014; Chui *et al*., 2016; Liu *et al*., 2017; Esmail & Suleiman, 2020; Rong *et al*., 2021; Darabi *et al*., 2020). Regardless of the terms that have been using across the world, it has to promote nature-based solutions (NBS) and suggesting the application of sustainable stormwater management facilities or components that can imitate the natural hydrological process. In stormwater management, the application of swale as one component in controlling surface runoff in terms of quantity and quality is a worldwide practice. Rong *et al*. (2021) for example have studied several different LID components namely vegetated swales, sunken green spaces, rain barrels, and combined methods in China where sponge cities concepts have become a new trend for urban construction. Similar to LID, a sustainable urban drainage system (SUDS) also has many components in managing stormwater in urban areas.

In SUDS, there are three different site locations (depending to the amount of runoff that will be cater) to construct suitable components. It means each component has a different ability in stormwater management and it is depending on the location it will construct. The locations are known as at source which means source of the surface runoff, site, and regional. Components that have been located in the regional area will manage a larger amount of surface runoff due to the bigger size of the catchment area. Components that are usually implemented at source of the runoff are grassed swale and green roofs. Example facilities for site areas that convey a larger amount of runoff than the source are on-site detention (OSD) whereas, for a regional area, detention or retention pond will be put into consideration. In SUDS practices, grass swales are considerably low-cost and easy to install. Grass swale is also easy and has less maintenance. Ekka *et al*. (2021) agreed that selections of swale type depends on several factors like funding for design, construction and operation, site constraints, and local climates. It is a norm that tropical climate areas always receive high rainfall depth throughout the year. Thus, a bigger size of swale is usually designed to convey a larger amount of surface runoff generated by the rainfall event. Failing to do so, it will lead to the flash flood in the downstream area. Notable that the wider size of swale will need a bigger area and cost also will increase due to land reclamation might be occurred. Therefore, a combination of grass swale and ecological subsurface or subdrainage module should be implemented as an alternative. This arrangement of design will improve this facilities' capability in slowing surface flow, recharge groundwater through flow infiltration, reduce peak flow, vegetation manage to reduce particulate pollutants, and increase dissolved oxygen due to the turbulence created in the subsurface modules significantly (Ayub *et al*., 2005; Mohammadpour *et al*., 2019).

Since Malaysia is a tropical climate country, it receives high rainfall depth that generated a high amount of stormwater. To avoid urban flash floods, the quantity and quality of surface runoff water need to control through the application of these combinations (swale and subdrainage module). The first project that implemented this type of design was known as Bio-ecological Drainage System (BIOECODS) which is located in Engineering Campus, Universiti Sains Malaysia. BIOECODS is a Malaysia pilot project related to SUDS and sponsored by the Department of Irrigation and Drainage Malaysia. The system was designed by River Engineering and Urban Drainage Research Centre (REDAC), USM. BIOECODS was also constructed to be a kick start and reference for Malaysian practitioners and the design is based on the Urban Stormwater Management Manual (MSMA) Guideline for Malaysia which was launched in 2001. Through BIOECODS that implemented MSMA, the guideline should be followed for new development to date. Besides surface grass swales, subdrainage modules underneath the swales in BIOECODS are designed as main components in the system (Zakaria *et al*., 2003). Rizalihadi & Safiana (2015) found that the density of vegetation had influenced the flow resistance in the surface swale, where the *Axonopus compressus* (cow grass) have been planted in BIOECODS.

Theoretically, module roughness in a different channel can be estimated using Manning's roughness coefficient (*n*) (Ab. Ghani *et al*., 2007; Kee *et al*., 2011; Pradhan & Khatua, 2018; Kamali *et al*., 2018). To estimate Manning's roughness coefficient in subdrainage modules, five parameters are needed namely hydraulic radius (R), channel width, flow depth, velocity and channel slope. To predict n for surface vegetated swales, a simple equation can be developed however the validity of the equation should be done through field measurement (Abd Elmoaty & El Samman, 2020). Roughness variability in Manning's equation also has been discussed by Tuozzolo *et al*. (2019). But studies related to the sub-drainage flow, and its parameters are very limited. Mechanisms of interactions between fluid flow and solid structure that create high-flow resistance and low-flow velocity in sub-drainage is also very few (Abdurrasheed *et al*., 2019). Experience gained through BIOECODS study it is challenging to evaluate flow depth in subdrainage modules due to the location of the flow is underneath of the surface swale except for the installation of related equipment has been made during the construction of subsurface drainage. As guidance in determining *n* in the subsurface channel, this paper is to discuss and develop a flow rating curve that summarizes the relationship between flow (Q) and water depth or flow depth (y) as one of the variables that influence flow capacity in a single module subdrainage. The present study also validated the suggested equation for two cases namely Gate Fully Open (GFO) and Gate Partially Open (GPO) of a modular channel by Mohammadpour *et al*. (2019).

2. Material and methods

The research was conducted in REDAC's Hydraulic Laboratory, Engineering Campus, Universiti Sains Malaysia, and the data have been used to validate the suggested equations by Mohammadpour *et al*. (2019) for gate fully open and gate partially open in the subsurface modular channel. Detail experiment setup is described in section 2.1 and 2.2.

2-1. Physical model setup

The experimental setup is the same as Ab. Ghani & Ayub (2020) where the experiments have been conducted in a 6-meter rectangular flume as shown in Figure 1. Single modules designed by REDAC with a dimension of 400mm x 435mm x 710mm and thickness of 17.5mm were used (Figure 2). Five numbers of these single modules were installed horizontally in series in the flume (Figure 3) to represent the real condition of the subdrainage modular channel underneath the swale. These modules were tag as Module 1 (M1), Module 2 (M2), Module 3 (M3), Module 4 (M4), and Module 5 (M5) from inlet to outlet respectively. To avoid turbulence and creating smooth flow throughout the 6m flume, one module was installed vertically as an energy dissipator at the inlet of the flume. Thus, velocity measurements in particular modules would be more accurate. A stainless-steel control gate also was installed at the end of the flume to mimic the subdrainage channel's conditions underneath and to create different flow depth (y) which is one of the important parameters in Manning's equation.

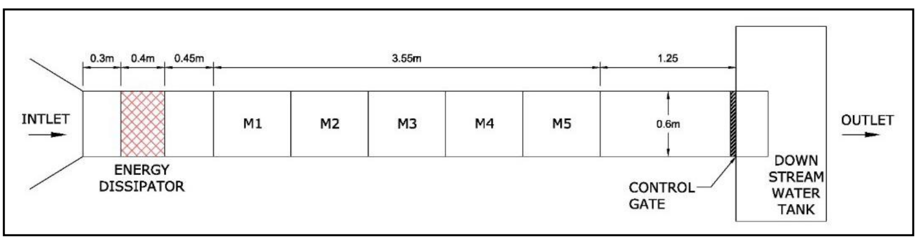

Fig. 1. Plan view of the experimental setup in the present study (not to scale)

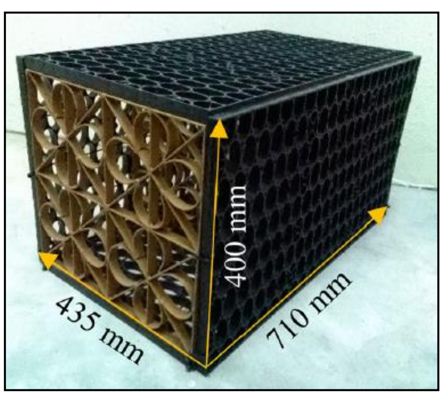

Fig. 2. Bunga Cengkih vertical part design for single REDAC module (Mohammadpour *et al*., 2019)

Fig. 3. Experimental setup in REDAC Physical Laboratory, (1) Installing single REDAC module horizontally; (2) Velocity measurement for gate fully open (GFO) and (3) Front view of gate partially open with 2cm height (GPO2)

Different flow depth (y) conditions created through this gate have been known as gate fully open (GFO), gate partially open (2cm) (GPO2) from the bed flume, and finally gate partially open (4cm) (GPO4) also from bed flume. Three bed slopes of 1:1000 (0.001), 1:750 (0.0013) and 1:500 (0.002), were applied in this experiment setup. Table 1 summarizes the condition of the experimental setup in the present study. By using a flowmeter, measurement of velocity and flow depth in each point of module 2 (M2), module 3 (M3), and module 4 (M4) were taken at 0.6y from the channel bed where y is flow depth (Figure 3). Equation 1 (Eq. 1) was used to calculate flow discharges whereas Equation 2 (Equation 2) was used to calculate Manning's roughness coefficient, *n* for the subdrainage module. Results from Eq. 2 have been used to validate the *n* value that was calculated through equations that have been developed by Mohammadpour *et al*. (2019) as shown in Equation 3 (Eq. 3) for case GFO and Equation 4 (Eq. 4) for case GPO:

$$Q = VA \qquad (1)$$

where, Q is the flow discharge (m^3/s), V is the velocity (m/s) and A (m^2) is the flow area of single module in flume:

$$n = \frac{R^{\frac{2}{3}} A}{Q} \sqrt{S} \qquad (2)$$

where R is the hydraulic radius, A isthe area, Q is the flow rate and S is the longitudinal slope:

Case GFO: $n=0.004(y/B)^{-0.456}$ (3) (Mohammadpour *et al*., 2019)

Case GPO: $n=0.723(y/B)^{1.202}$ (4) (Mohammadpour *et al*., 2019)

where *y/B* is the flow depth ratio.

2-2. Data Collection and Analysis

By using flow meter and measuring tape, velocity and flow depth of each case (GFO, GPO2 and GPO4) with different slopes at M2, M3 and M4 were recorded. The measurements of the velocity and flow depth have been taken three times at each location. Data recorded have been use as input to calculate flow. All data were analysed by using Microsoft Excel 2013.

3. Results

Through these experiments, it shows gate opening conditions may influence the flow depth (y) and flow capacity in a single subdrainage channel. As summarized in Figure 4, in different gate openings, flow is inversely proportionate with flow depth with R^2=0.97. GFO was recorded to has the highest value of flow capacity followed by GPO4 and GPO2. This is due to the free flow occurred in GFO case but not in GPO4 and GPO2.

To validate Manning's equation developed by Mohammadpour *et al*. (2019), results from *n* values in modular channel obtained from the present study were compared. The present study shows gate opening at the outlet of the flume does affect the *n* value. The lowest value of *n* is recorded in a range 0.0025-0.0030 with GFO condition and *n* value is increased for condition GPO4 ranging 0.0038-0.0054. The highest value of n was obtained from the GPO2 condition and the value in the range 0.011-0.022. Thus, the finding by Mohammadpour *et al*. (2019) is confirmed through the present study where the GPO condition may lead to higher values of *n* compared to the GFO condition. This study also found that Manning's n is inversely proportionate with velocity (V) which has the same trend as Mohammadpour *et al*. (2019). Table 2 summarizes the results of Manning's *n* value in the present study by using Eq. 2 and the equation developed by Mohammadpour *et al*. (2019) which is Eq. 3 (GFO condition) and Eq. 4 (GPO condition). Manning's *n* equation (Eq. 2) and new equation (Eq. 3 and Eq. 4) are successful to validate where R^2=0.77 and it suggests that Eq. 3 and Eq. 4 can be applied to determine or calculate the value of Manning's *n* for sub-drainage channel. The best condition for the module to convey the maximum flow is during free flow which is the GFO condition. Whereas GPO which simulated submerged flow conditions may cause an increase in flow resistance due to submerged condition increase. It is due to the Manning's *n* value is high as resulted from formation of backwater and increasing in flow depth.

Table 1. Experimental setup condition in the present study

Case	Remark	Slope
GFO	Gate fully open	0.001, 0.0013 & 0.002
GPO2	Gate partially open with height 2cm from bed	0.001, 0.0013 & 0.002
GPO4	Gate partially open with height 4cm from bed	0.001, 0.0013 & 0.002

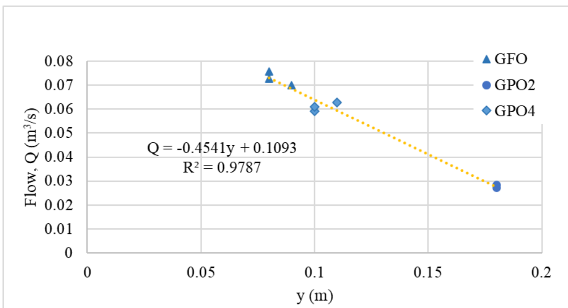

Fig. 4. Correlation between flow capacity in a subdrainage single module and flow depth

Table 2. Summary of Manning's n calculation for the subdrainage single module

Case	Slope	y	A (m^2)	R (m)	V m/s	Q m^3/s	Manning's values obtained from Eq. 2 *n*	Manning's Equation (Eq. 3 and Eq. 4) by Mohammadpour *et al.* (2019)	Difference (%)
GFO								n=0.004(y/B)$^{-0.456}$	
	0.001	0.09	0.0365	0.0608	0.4078	0.0701	0.0025	0.008162	-
	0.0013	0.08	0.0344	0.0583	0.4233	0.0728	0.0025	0.008612	0.6
	0.002	0.08	0.0344	0.0583	0.4400	0.0757	0.0030	0.008612	17.6
GPO								n=0.723(y/B)$^{1.202}$	
GPO2 (2cm)	0.001	0.18	0.0774	0.0980	0.1644	0.0283	0.0182	0.253832	-
	0.0013	0.18	0.0795	0.0994	0.1589	0.0273	0.0223	0.253832	20.1
	0.002	0.11	0.0403	0.0651	0.1422	0.0245	0.0118	-	
GPO4 (4cm)	0.001	0.10	0.0430	0.0683	0.3433	0.0591	0.0038	0.12523	-
	0.0013	0.10	0.0430	0.0683	0.3544	0.0610	0.0042	0.12523	9.9
	0.002	0.11	0.0451	0.0705	0.3644	0.0627	0.0054	0.140431	35.2

4. Conclusion

The present study is carried out to evaluate the flow performance of a single module and validate the new Manning's *n* equation developed by Mohammadpour *et al*. (2019). Flow capacity in a subdrainage channel with a single module can be estimated through a developed rating curve where three conditions (GFO, GPO2, and GPO4) were studied in the present experiments. Noticeable that flow conveys through single REDAC module created the lower Manning's *n* values with free-flow condition (0.0025-0.0030) followed by submerged flow condition, GPO4 (0.0038-0.0054) and, GPO2 (0.011-0.022). The equation developed by Mohammadpour *et al*. (2019) was verified where R^2 is 0.77. It confirmed that both equations are convenient simplifications of calculating value Manning's *n* in subdrainage channel condition without using a flow meter and digging the constructed or built subdrainage channel. This can simplify the method to evaluate Manning's *n* value. The best condition for the modules to act as a flow conveyance is during free flow and it is confirmed through this study. Submerged flow conditions as simulated by the GPO in the present experimental studies show that flow resistance increases with submerged conditions. This suggests that the application of the REDAC module as a subdrainage channel for swale can reduce the stormwater quantity in urban drainage due to the low Manning's coefficient gained in this study. Implementation of swale with REDAC module as subdrainage channel for the newly developing area is very competent in stormwater management to combat flash floods.

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