UNIVERSITI SAINS MALAYSIA

DETERMINATION OF FLOW RESISTANCE IN MODULAR OPEN CHANNEL

by

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LIST OF SYMBOLS

A	cross sectional area [m^2]
B/Y	aspect ratio
c	sediment concentration [kg/m^3]
C	Chezy coefficient
d	sediment size [m]
d_0	diameter of pipe [m]
d_R	rainfall duration [hr]
D_H	hydraulic diameter
f	friction factor
F	frequency [Hz]
Fr	Froude number
g	gravitational acceleration [m/s^2]
h_f	frictional loss [m]
I	rainfall intensity [mm/hr]
K_n	conversion constant [$m^{1/2}/s$]
L	dimension of length [m]
l	characteristic length [m]
μ/D	viscous forces
n	Manning roughness coefficient [$m^{1/3}/s$]
N	number of samples
n_g	new resistance coefficient [$m^{1/6}$]
v	kinematic viscosity [m^2/s]
O_i	observed values

$\bar{O}$	mean of observed values
P	wetted perimeter [m]
P_d	rainfall depth [mm]
P_i	predicted values
$\overline{P}$	mean of predicted values
q	unit of flow discharge [m^2/s]
Q	flow rate [m^3/s]
R	hydraulic radius [m]
R^2	coefficient of determination
Re	Reynolds number
S	slope of energy line
T	temperature of water [^0C]
V	flow velocity [m/s]
V_R	rainfall volume [m^3]
VR	product of velocity and hydraulic radius [m^2/s]
$V\rho$	inertial forces [kgm^2/s^2]
Y	flow depth [m]

LIST OF ABBREVIATION

ARI	Average Recurrence Interval
BIOECODS	Bio-Ecological Drainage System
BMPs	Best Management Practices
DID	Department of Irrigation and Drainage
DO	dissolved oxygen
GP	Genetic Programming
GPT	gross pollutant trap
KK2	Taiping Health Clinic Type 2
OSD	on-site detention
MSMA	Urban Stormwater Management Manual for Malaysia
REDAC	River Engineering and Urban Drainage Research Centre
RMSE	root mean square error
SUDS	Sustainable Urban Drainage System
SPSS	Statistical Package for the Social Sciences
USM	Universiti Sains Malaysia

PENENTUAN RINTANGAN ALIRAN DALAM SALURAN TERBUKA BERMODULAR

ABSTRAK

Tangki simpanan bermodular adalah suatu sistem modular ringan yang biasanya digunakan sebagai tangki simpanan bawah tanah untuk menakung air hujan. Tangki ini mempertingkatkan penggunaan semula air hujan, penyusupan air permukaan dan peningkatan kualiti air. Dalam sistem saliran bandar mapan yang direkabentuk oleh Pusat Penyelidikan Kejuruteraan Sungai dan Saliran Bandar (REDAC), Universiti Sains Malaysia (USM), tangki simpanan bermodular ini digunakan sebagai saliran bawah tanah bersepadu dengan saluran berumput. Terdapat dua jenis saluran bermodular yang telah dikaji iaitu saluran bermodular yang sedia ada dan saluran bermodular yang baru direka. Saluran-saluran ini dikenali sebagai Saluran Bermodular Jenis A dan Saluran Bermodular Jenis B masing-masingnya. Dalam kajian ini, 54 set data kajian dan data lapangan telah dianalisa untuk mengkaji ciri-ciri hydraulik bagi Saluran Bermodular Jenis A. Sementara itu, 30 set ujian eksperimen telah dijalankan untuk mengkaji aliran dalam Saluran Bermodular Jenis B. Dalam kajian ini, penyiasatan mengenai variasi pekali Manning n dengan parameter hidraulik telah dibentangkan. Analisa menunjukkan bahawa terdapat perkaitan yang rapat antara pekali Manning n dan nombor Froude dengan pekali penentuan yang melebihi 0.9. Satu langkah perekaan saluran bermodular, iterasi, telah dicadangkan dengan menggunakan hubungan antara pekali Manning n dan nombor Froude. Selain itu, persamaan yang dipermudahkan dengan hanya menggunakan nisbah aspek dan kecerunan saluran dihasilkan daripada regresi tak linear berganda dan pengaturcaraan genetik. Ia menunjukkan bahawa ramalan dengan

menggunakan pengaturcaraan genetik mempunyai kecenderungan ramalan yang kekurangan bagi kadar aliran untuk data lapangan. Maklumat yang dilaporkan dalam kajian ini boleh digunakan untuk meramalkan ciri-ciri hidraulik saluran bermodular di bawah keadaan yang berbeza.

DETERMINATION OF FLOW RESISTANCE IN MODULAR OPEN CHANNEL

ABSTRACT

Storage tank module is a lightweight modular system which commonly used as underground storage tank for rainwater harvesting. This storage tank module promotes reuse of rainwater, infiltration of surface water and water quality improvement. In sustainable stormwater drainage system designed by River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia (USM), this storage tank module was used as underground conveyance conduit integrated with grassed swale. There are two types of modular channel investigated in this study which is the existing and newly designed modular channel which is known as Modular Channel Type A and Modular Channel Type B respectively. In this study, a total number of 54 sets of experimental and field had been analyzed in order to investigate the hydraulic characteristics of Modular Channel Type A. Meanwhile, a total number of 30 sets of experimental tests were carried out in investigating flow in Modular Channel Type B. Investigation concerning the variation of Manning's *n* with hydraulic parameters which include of flow depth, flow velocity, flow rate, Froude number and Reynolds number were also presented in this study. The analysis indicated that there were good correlations between Manning's *n* and Froude number with correlation of coefficient (R^2) more than 0.93. A design step of modular channel was proposed by utilizing the relationship between Manning's *n* and Froude number using iteration. Apart from this, simplified equations by using only aspect ratio and channel slope were developed by using multiple non-linear regression and genetic programming. It shows that prediction by using genetic programming tends to underestimate flow rate

for field data. Information reported in this study can be used to estimate the hydraulic characteristics of modular channel under different condition.

CHAPTER 1

INTRODUCTION

1.1 Background

In Malaysia, conventional stormwater drainage systems which are constructed using concrete material have been widely used. However, this practice brings a significant impact on the environment as a whole. The conventional stormwater drainage systems increase pollution because silt, oils and other pollutants are carried straight to streams and rivers. Apart from this, the conventional stormwater drainage systems tend to cause flooding as runoff is being conveyed to watercourses directly in shorter duration and have less infiltration into the ground. Flooding has caused a large number of casualties, disease epidemics, property and crop damage and other intangible losses annually (Liu and Chan, 2003). The rapid disposal of runoff allows little time for natural water treatment and limits the recharge of groundwater aquifers. This has prevented the rainfall to be infiltrated into the soil and finally causing a big amount of runoff to be conveyed to streams and rivers.

With regards to the problems stated previously, it is obvious that this developing world needs a long term environmental friendly and sustainable drainage system which can reduce the impact of urbanization in the stormwater quantity and quality issues. Best Management Practices (BMPs) and Sustainable Urban Drainage System (SUDS) which focus on water quantity and water quality control are two popular concepts which are being widely implemented currently. Department of Irrigation and Drainage Malaysia (DID) has produced an urban drainage manual which known as Urban Stormwater Management Manual for Malaysia (MSMA) in year 2000 in line with the concept of BMPs which focuses on ‘control at source’ approach (DID, 2000). This manual emphasizes the utilizing of a variety of different control measures which aims to reduce water pollution problems, conserve natural water resources and also enhance the amenity value of watercourses in the urban environment, to achieve Zero Development Impact Contribution. This urban drainage manual is being effectively implemented from Jan 2001.

Realizing the importance of practicing BMPs in Malaysia, Universiti Sains Malaysia (USM), in collaboration with the DID Malaysia, have constructed the pilot Bio-Ecological Drainage System (BIOECODS) at the USM Engineering Campus, in Nibong Tebal, Penang. BIOECODS represents an alternative to the traditional hard engineering-based drainage system with the application of grass swales, subsurface modular channel, dry ponds, wet pond, detention pond, and constructed wetland to manage stormwater quantity and quality for the campus. BIOECODS is an effective system in flow attenuation, in the reduction of runoff pollution as well as in the increment of environmental amenity value (Zakaria et al., 2003).

Sustainable Urban Drainage System (SUDS) is a new environmentally friendly way of dealing with surface water runoff in water quantity and quality control, which minimizes the problems associated with conventional drainage practice. To this end, River Engineering and Urban Drainage Research Centre (REDAC), USM had designed a drainage system for Taiping Health Clinic Type 2 (Ab. Ghani et al., 2008). The devices provided in this drainage system include perimeter drain, grassed swale with subsurface modular channel, underground detention storage, external drain, dry pond and on-site stormwater detention (OSD).

Apart from this, gross pollutant traps (GPT) were provided at both entrance of OSD in the study site.

The grassed swale system was designed for 5-year Average Recurrence Interval (ARI) with longitudinal slope of 1:500. It consists of surface swale and subsurface modular channel in parallel arrangement. The modular channel is enclosed within permeable geotextile with screening ability of 0.38 mm to prevent sediment from entering the drainage system. It is overlaid by a layer of porous media (gravel) with clean river sand at both sides and bottom part as well as a layer of top soil for grass planting (Figure 1.1). Cow grass species with shallow root is planted on the surface swale for both water quantity and quality control. Firstly, modular channel receives infiltrated stormwater runoff from grassed swale surface. Water infiltrated into modular channel will then be conveyed to the outlet.

Storage tank module is a lightweight modular system which commonly used as underground storage tank for rainwater harvesting. This storage tank module promotes reuse of rainwater, infiltration of surface water and water quality improvement. Storage tank module is mostly applied as rainwater harvesting system where clean, clear and odorless water will be collected from rainwater through infiltration and filtration process for various purposes. The other applications of storage tank module in stormwater management include on site detention, filtration pond, bio remediation and etc. In BIOECODS, storage tank module is applied as subsurface modular channel in conveying stormwater runoff.

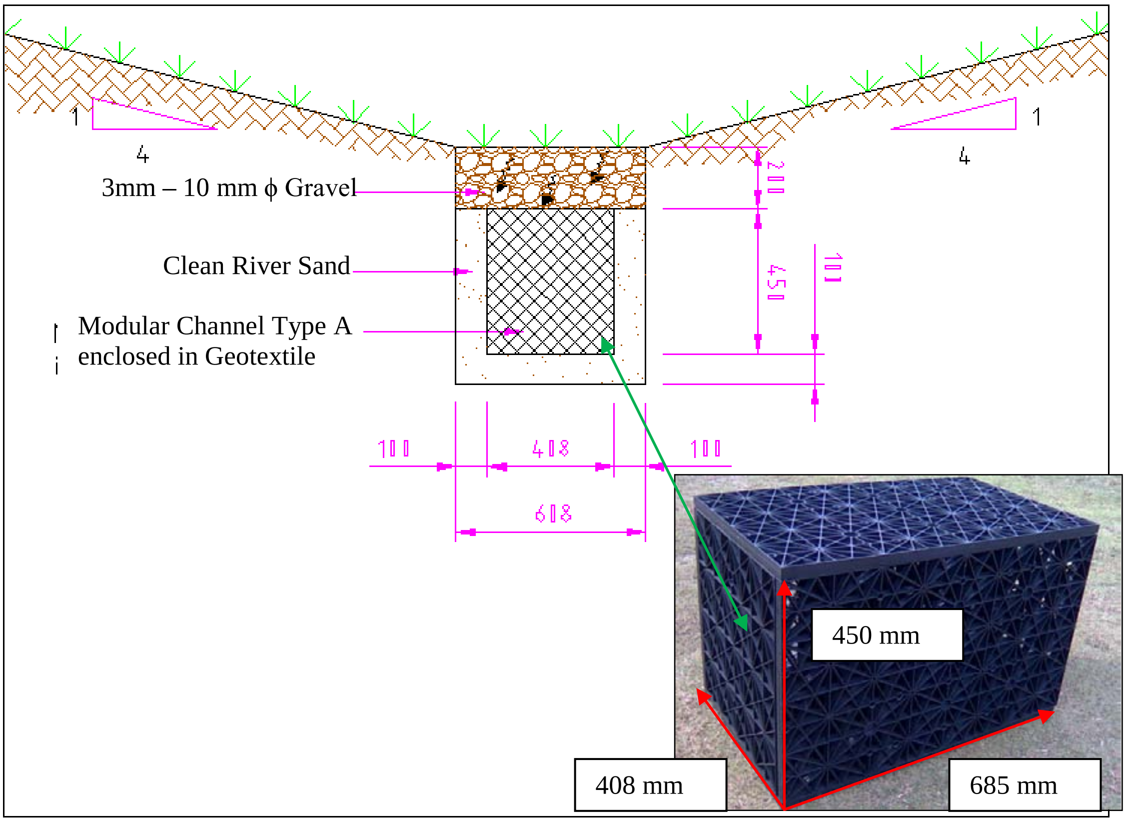

Figure 1.1: Typical section for grassed swale at Taiping Health Clinic Type 2

1.2 Problem Statements

The construction of grassed swale with subsurface modular channel has been encouraged as another option in controlling stormwater runoff. However, there is a lack of information for the designing of modular channel as conveyance conduit. Flow resistance is an important parameter in designing a conveyance system. The flow resistance of modular channel is unknown as this system is not designed for conveyance system at the initial purpose. Apart from this, the understanding of hydraulic characteristics of modular channel as conveyance conduit is important to provide information for future design. Therefore, this study which investigates the hydraulic characteristics and flow resistance is able to improve the understanding of modular channel as conveyance conduit.

1.3 Objectives

The aim of this study is to gain an improved understanding on the hydraulic characteristics and flow resistance for modular channel as conveyance conduit. The detailed objectives of this study include:

(a) To determine the hydraulic characteristics for two types of modular channel; and

(b) To develop equations in estimating the Manning's *n* for two types of modular channel.

1.4 Scopes of Present Study

The present study focuses on the hydraulic characteristics and flow resistance of modular channel as conveyance conduit. Both laboratory and field data were collected. Laboratory tests were conducted at Physical Modeling Laboratory of River Engineering and Urban Drainage Research Centre (REDAC) at Universiti Sains Malaysia using a re-circulating flume with a working section length of 5.90 m. Two types of modular channel namely Modular Channel Type A and Modular Channel Type B were tested in this study. All laboratory tests were conducted under uniform flow condition. The laboratory tests were carried out under different slopes condition and various flow rates. Apart from this, tailgate was applied in order to investigate the behavior of flow in modular channels under storage effect.

Field study was carried out at Taiping Health Clinic Type 2 (Figure 1.2). Field study on the modular channel had been chosen at Taiping Health Clinic because of the following factors:

(a) Consists of Modular Channel Type A in grassed swale system;

(b) Small-scale catchment area (2.2 ha);

(c) Newly constructed Sustainable Urban Drainage System (SUDS) which completed in year 2005; and

(d) Taiping is the wettest area in Malaysia.

Figure 1.2: Location of Taiping Health Clinic Type 2

1.5 Outline of Thesis

This thesis consists of six chapters. Following the introductory chapter, Chapter 2 presents relevant studies for experimental and field works on flow resistance in various types of open channel.

Chapter 3 describes the research methodology which includes experimental apparatus and procedures adopted in the present investigation, with the details of the test flume, measurement techniques, and modular channel characteristic. It also describes the field study which covers the site location and field data measurement techniques.

The hydraulic characteristics in two types of modular channel investigated in this study are depicted in Chapter 4. This chapter discusses the relationship between various hydraulic parameters to describe the characteristics of flow inside modular channels.

Chapter 5 entitled the "Development of Manning's *n* Equation for Modular Channel" presents the analysis in obtaining the most suitable Manning's *n* equation for modular channel. It also presents the sensitivity analysis for dimensionless parameters in influencing Manning's *n* for modular channel. Simplified equations developed by using multiple non-linear regression and genetic programming are discussed.

Finally, Chapter 6 summarizes the conclusions obtained from the present study and suggests several recommendations for future research work in light of the present study. At the end of the thesis, a list of relevant references and appendices are given.

CHAPTER 2

FLOW RESISTANCE IN OPEN CHANNEL

2.1 Introduction

Before formulating the methodology in this study, relevant past studies related to flow resistance in open channel were studied in order to obtain a deep understanding for related study. Flow resistance in open channel is well described by Yen (1992a). Flow in open channels always subject to resistance and energy dissipation. Yen (2002) stated that Rouse (1965) classified flow resistance into four components namely: (a) surface or skin friction, (b) form resistance or drag, (c) wave resistance from free surface distortion, and (d) resistance associated with local acceleration or flow unsteadiness. Numerous studies had been undertaken in the past on flow resistance in open channels either constructed or natural channels, precast ecological concrete blocks, vegetated channels, wetlands, meandering channels, alluvial and gravel beds channels as presented in Bakry (1992), Rouhipour et al. (1999), Tsihrintzis and Madiedo (2000), Jarvela (2002), Lee and Ferguson (2002), James et al. (2004), Diaz (2005), Ab. Ghani et al. (2007), Wilson (2007), Wu (2008), Chen et al. (2009), Nayak et al. (2009), Chang et al. (2010), Fathi-Moghadam (2010), and Fenton (2010). Several publications summarize theory of flow resistance in open channel such as Chow (1959), Yen (1992a), Yen (1992b), and Yen (2002).

2.2 Open Channel Flow Resistance

There are three common equations relating the open channel flow velocity (V) to resistance coefficient namely Chezy formula, Manning formula, and Darcy-Weisbach Formula.

2.2.1 Chezy Formula

The first uniform flow formula was developed by Antoine Chezy as early as 1769. This formula is known as Chezy formula which is usually expressed as (Chow, 1959):

$$V = C\sqrt{RS} \tag{2.1}$$

where V is the mean velocity in m/s, R is the hydraulic radius in m, S is the slope of the energy line, and C is a factor of flow resistance, which known as Chezy's C. There are three important formulas to determine Chezy's C namely, G.K. Formula, Bazin Formula, and Powell Formula (Chow, 1959).

2.2.2 The Manning Formula

Another widely practiced uniform flow formula is the Manning formula which is being expressed by the following equation (Chow, 1959):

$$V = \frac{K_n}{n} R^{2/3} S^{1/2} \tag{2.2}$$

where n is the coefficient of roughness which known as Manning's n, V is the mean velocity in m/s, R is the hydraulic radius in m, S is the slope of the energy line, K_n = 1 $m^{1/2}/s$ for V and R in SI units or 1.486 $ft^{1/3}$-$m^{1/6}/s$ for English units, and $\sqrt{g}$ for dimensionally homogeneous Manning formula stated by Yen (1992). In applying the Manning formula, the greatest difficulty lies in the determination of roughness coefficient. Estimating the flow resistance in open channels is very important as it has a significant effect on the conveyance of the channel. Tables of Manning's n are given in manuals of hydraulic design such as Chow (1959), FHWA (1961), FHWA (1979), FHWA (1988), FHWA (1996), and Fisher & Dawson (2003). There are also a large number of formulas developed to calculate the Manning's *n* in natural channels. The following include some methods of the calculation:

(a) Barnes (1967) has presented colour photographs and descriptive data for 50 stream channels, including the average values of the Manning roughness coefficient for each channel. Manning's *n* values can be determined by taking into account of the factors affecting, by referring to a table of typical roughness coefficients for channels and by examining and becoming acquainted with the geometry or appearance of some typical channels whose roughness coefficients are known. However, the lack of complete similarity in channel conditions and geometry from stream to stream makes it difficult to estimate channel roughness from illustrations and stereoscopic slides.

(b) Limerinos (1970) had studied the determination of the Manning's *n* from measured bed roughness in natural channels. An equation for natural alluvial channels was developed as:

$$n = \frac{0.0926 R^{1/6}}{1.16 + 2.0 \log\left(\frac{R}{d_{84}}\right)} \tag{2.3}$$

(c) A total number of seven equations available to predict values of Manning's *n* for rivers were stated in the study done by Ab. Ghani et al. (2007). These equations had been categorized into three component:

(i) Equations based on bed sediment size

Strickler (1923) : $n = \frac{1}{21.1} d_{50}^{1/6}$ (2.4)

Meyer-Peter & Muller (1984) : $n = \frac{1}{26} d_{90}^{1/6}$ (2.5)

Lane & Carlson (1953) : $n = \frac{1}{21.14} d_{75}^{1/6}$ (2.6)

(ii) Equations based on ratio of *R* or *Y* over sediment size

Limerinos (1970) : $n = \dfrac{0.113 R^{1/6}}{0.35 + 2.0 \log_{10}\left(\dfrac{R}{d_{50}}\right)}$ (2.7)

Bray (1979) : $n = \dfrac{0.113 Y^{1/6}}{1.09 + 2.2 \log_{10}\left(\dfrac{Y}{d_{50}}\right)}$ (2.8)

(iii) Equations based on *S*

Brownlie(1983):

$$n = \left[1.893\left(\frac{R}{d_{50}}\right)^{0.1374} \times S^{0.1112}\right] \times 0.034 \times (d_{50})^{0.167} \quad (2.9)$$

Bruschin (1985): $n = \dfrac{d_{50}^{1/6}}{12.38} \times \left(\dfrac{R}{d_{50}} \times S\right)^{1/7.3}$ (2.10)

where *d* is the representative sediment size in metres/m (d_{50}, d_{75} or d_{90}), *R* is the hydraulic radius in meters, *Y* is the flow depth in metres/m and *S* is the slope of energy line.

(d) Jarret (1990) has developed an equation in predicting Manning's *n* in natural mountain channels with cobble or boulders bed material as:

$$n = 0.32 S^{0.30} R^{-0.16} \tag{2.11}$$

where *S* is the slope of energy line and *R* is hydraulic radius in m.

Although the value of Manning's *n* are listed to be a constant in the tables, however in reality, a channel do not have a constant resistance coefficient under all occasions and conditions. In fact, the value of Manning's *n* is highly depends on a number of factors. Chow (1959) had listed out some factors affecting the value of Manning's *n* which include:

(a) Surface Roughness – Surface roughness is presented by the size and shape of the grains of the material forming the wetted perimeter and producing a retarding effect on the flow. In general, fine grains result in a relatively low value of Manning's *n* and vice versa.

(b) Vegetation – The effect of vegetation towards value of Manning's *n* depends on height, density, distribution and type of vegetation.

(c) Channel Irregularity – The channel irregularities include irregularities in wetted perimeter and variations in cross section, size, and shape along the channel length. In general, a gradual and uniform change in cross section, size and shape will not appreciably affect the value of Manning's *n*, but an abrupt change or alternation of small and large sections results the needs of large value of Manning's *n*.

(d) Channel Alignment – Smooth curvature with large radius will give a relatively low value of Manning's *n*, whereas sharp curvature with severe meandering will increase Manning's *n*.

(e) Silting and Scouring – In general, silting may change a very irregular channel into a comparatively uniform channel and thus decrease the value of Manning's *n*. Scouring may do the reverse and increase the value of Manning's *n*.

(f) Obstruction – The presence of log jams and bridge piers tends to increase Manning's *n.*

(g) Size and Shape of Channel – An increase of hydraulic radius may either increase or decrease the Manning's *n*. Though, there is no strong evidence about this factor as an important factor in influencing the Manning's *n.*

(h) Stage and Discharge – The Manning's *n* value in most streams decreases with increase in stage and in discharge.

(i) Seasonal Change – The value of Manning's *n* may increase in the growing season and diminish in the dormant season.

(j) Suspended Material and Bed Load – The suspended material and the bed load, whether moving or not moving, would consume energy and cause head loss or increase the apparent channel roughness.

Cowan (1956) developed a procedure for estimating the value of Manning's *n* for a channel by considering the factors influencing Manning's *n*. Thus, the value of Manning's *n* can be computed by:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5 \tag{2.12}$$

where n_0 is a basic *n* value for a straight, uniform, smooth channel in the natural material involved, n_1 is a value added to n_0 to correct for the effect of surface irregularities, n_2 is a value for variations in shape and size of the channel cross section, n_3 is a value for obstructions, n_4 is a value for vegetation and flow conditions, and m_5 is a correction factor for meandering of channel. The value of n_0 to n_4 and m_5 can be referred to Chow (1959).

Several researches on Manning's *n* for various type of flume condition were done (Chang et al., 2010; Nalluri & Adepoju, 1985). Methodology in carrying out experimental tests was reviewed (Ab. Ghani, 1993; Wilson & Horritt, 2002; Chang et al., 2010; Vongvisessomjai et al., 2010). In the research of sediment transport in sewers done by Ab. Ghani (1993), a good description of experimental work was established. This study extended the available data in rigid boundary conditions to include effects of surface roughness and pipe size. Preliminary analyses of flow resistance for clean pipes and pipe with deposited beds were done by conducting experiments where 219 experiments were carried out in smooth pipes and the other 126 experiments were performed in rough clean pipes. In general, the values of Manning's *n* were constant over the range of Reynolds numbers studied. In the research study done by Vongvisessomjai et al. (2010), a well established laboratory experiments set up was described. They reviewed the existing self-cleansing design criteria for sewers based on minimum velocity and minimum bed shear stress. Uniform flow in the pipe channel was achieved by adjusting the tail water sluice gate such that the water depth in pipe was uniform and constant with time. Velocity measurements were done by taking the velocities at surface, middle depth and near bottom and average to obtain the mean velocity. For the experiment with clear water without sediment, the Manning's *n* was found to be 0.0125.

Chang et al. (2010) had done the analysis of hydraulic characteristics and estimation of Manning's *n* for an artificial materials-precast ecological concrete blocks developed in their research through hydraulic model experiments as shown in Figure 2.1. The Manning's *n* for this material is obtained between 0.0167 – 0.0437 in various discharge conditions.

Figure 2.1: Precast ecological concrete block model and its test in flume (Chang et al., 2010)

2.2.3 Darcy-Weisbach Formula

Darcy-Weisbach formula was developed primary to describe the pipe flow resistance which is given as:

$$h_f = f \frac{L}{d_0} \frac{V^2}{2g} \tag{2.13}$$

where h_f is the frictional loss in m for flow in the pipe, f is the friction factor, L is the length of the pipe in m, d_0 is the diameter of the pipe in m, V is the velocity of flow in m/s, and g is the acceleration due to gravity in m/s^2. This equation is then expressed in open channel flow as:

$$V = \sqrt{\frac{8gRS}{f}} \tag{2.14}$$

This equation can be applied to uniform and nearly uniform flows in open channels. Among the three formulas, only friction factor is expressed in terms of the Reynolds number (Chow, 1959) for all flow states namely laminar, transitional or turbulent. From Equation 2.1, 2.2 and 2.14, the resistance coefficients can be related as:

$$\sqrt{\frac{f}{8}} = \frac{n}{R^{1/6}}\frac{\sqrt{g}}{K_n} = \frac{\sqrt{g}}{C} = \frac{\sqrt{gRS}}{V} \tag{2.15}$$

Therefore, by knowing only one of the resistance coefficients, the other form of resistance coefficient can be computed. Yen (1992a) stated that the Manning formula in Equation 2.2 can be modified by replacing the coefficient of 1.486 (English units) or 1 (SI units) by $\sqrt{g}$ such that:

$$V = \frac{\sqrt{g}}{n_g} R^{2/3} S^{1/2} \tag{2.16}$$

In Equation 2.15, it shows that the new Manning's n (n_g) has the dimension of $L^{1/6}$, where L represents dimension of length. Therefore, the dimensionless form of n_g can be expressed by $n_g / R^{1/6}$.

These three traditional formulas are widely used in governing the flow resistance in open channel, however, some researchers pointed out the limitation of these formulas under specific conditions. It is not suitable to apply Manning equation in laminar and transitional state of flow as this equation was developed for fully turbulent flow in open channels (Chow, 1959; Kadlec, 1990). James et al. (2004) had derived an alternative equation to determine the flow resistance of emergent vegetation instead of using the Manning formula by introducing the stem drag coefficient in the equation. A new velocity formula, in the form of a modified Manning equation, is proposed for flow prediction in alluvial channels (Yu and Lim, 2003).

2.3 Hydraulic Parameters

Several studies had been done in order to investigate the relationship between flow resistance with appropriate hydraulic parameters such as Reynolds number (*Re*), Froude number (*Fr*), flow depth (*Y*), flow velocity (*V*), flow rate (*Q*), hydraulic radius (*R*), slope (*S*), product of velocity and hydraulic radius (*VR*) and etc. Some of the hydraulic parameters were defined in the following sections.

2.3.1 Reynolds Number

The flow regime of fluid is being identified by calculating Reynolds number (*Re*) of the fluid. Reynolds number is a dimensionless number that gives a measure of the ratio of inertial forces ($V\rho$) to viscous forces (μ/D) which quantifies the relative importance of these two types of forces for given flow conditions. Reynolds number for a rectangular or square open channel is defined by the following equation (Chow, 1959):

$$Re = \frac{Vl}{\upsilon} \qquad (2.17)$$

where V = mean velocity (m/s); l is the characteristic length (m); v = kinematic viscosity (m^2/s). Chanson (2004) applied hydraulic diameter, D_H instead of characteristic length, l in finding the Reynolds number by using Equation 2.17. Hydraulic diameter which also known as equivalent pipe diameter is defined as:

$$D_H = 4R = 4\frac{A}{P} \tag{2.18}$$

Where R = hydraulic radius (m); A = cross sectional area (m^2); P = wetted perimeter (m). Therefore, according to Equation 2.17 and Equation 2.18, Reynolds number will be derived as:

$$Re = \frac{4VA}{\upsilon P} \tag{2.19}$$

The dimensionless Reynolds number is an important parameter in the equations that describes whether flow conditions lead to laminar or turbulent flow. The values of Reynolds number which differentiate the flow type are described in Table 2.1.

Table 2.1: Type of flow with different value of Reynolds Number

Flow Type	Laminar	Transitional	Turbulent
Open Channel	$Re < 2000$	$2000 < Re < 4000$	$Re > 4000$
Pipe	$Re < 500$	$500 < Re < 2000$	$Re > 2000$

2.3.2 Froude Number

The effect of gravity upon the state of flow is represented by a ratio of inertial forces to gravity forces. This ratio is given by the Froude number (*Fr*). Froude number is a function of velocity and water depth which had given in the following equation (Chow, 1959):

$$Fr = \frac{V}{\sqrt{gY}} \tag{2.20}$$

where V is the velocity of flow in m/s, g is the acceleration of gravity in m^2/s, and Y is the depth of the flow section in m. Froude number relates to the state of flow is described in Table 2.2.

Table 2.2: State of flow described by Froude Number

Froude Number, Fr	State of Flow	Description
$Fr = 1$	Critical	Flow celerity equals to flow velocity
$Fr < 1$	Subcritical	Slow flow – tranquil and streaming
$Fr > 1$	Supercritical	High velocity – rapid, shooting, and torrential

By substituting *Fr* into Equation 2.2, Diaz (2005) had simplified that for wide channel with shallow flow depth where hydraulic radius can be defined as water depth:

$$n = \frac{g^{-1/2} Y^{1/6} S^{1/2}}{Fr} \tag{2.21}$$

Equation 2.21 is acceptable for the low flow depth/width ratio. The Manning's *n* was observed to be depended on sixth root of the water depth, square root of the slope and inversely proportional to the Froude number.

2.4 Relationship of Manning's *n* with Hydraulic Parameters

Regarding the importance of all the factors in determining the value of Manning's *n*, many studies relating factors influencing Manning's *n* were done (Gilley et al., 1990; Jarrett, 1990; Bakry, 1992; Rouhipour et al., 1999; Tsihrintzis & Madiedo, 2000; Diaz, 2005; Wilson, 2007; Chen et al., 2009; Nayek et al., 2009; Chang et al., 2010; Zhang et al., 2010). Most of these studies of flow resistance investigate the variation of flow in vegetated bed channels; some were done on gravel-bed channels, wetlands, natural rivers and meandering channels.

Diaz (2005) had analyzed the Manning's *n* for small-depth flows on natural-vegetated beds. This research was done in two phases, the first in a laboratory channel with artificial vegetation and the second in natural bed. It proved that the Manning's *n* decreases with increase in flow depth and increases with increment in bed slope. The same results were also found by Jarrett (1990), where onsite surveys and 75 current-meter measurements of discharge were made on 21 mountain rivers in Colorado. Apart from this, in the research study for estimation of Manning's *n* on precast concrete blocks which done by Chang et al. (2010), results indicate that the Manning's *n* are in inverse proportion to the discharges and flow depths and in proportion to the bed slopes. They also proved that Manning's *n* is inverse proportion to the flow velocity. Manning's *n* was observed to increase with decreasing flow depth reaching an asymptotic constant at lower levels of vegetation submergence (Wilson, 2007). Besides that, De Doncker et al. (2009) studied the relation between flow discharges with roughness coefficient due to weed growth of River As. They found out that lower discharges correspond with higher Manning's *n*.

Rouhipour et al. (1999) examined differences in resistance coefficients in relation to flow velocity using both laboratory and field data. They had drawn a relationship between Manning' *n* with velocity which showed that flow velocity was related to Manning's *n* to a power of -0·65 rather than the theoretical value of -1 as given in Manning's equation. In the study done by Gilley et al. (1990), Manning's *n* was found to decrease with increase in Reynolds number for the analysis of hydraulic characteristics of rills at 11 sites located in United States.

Zhang et al. (2010) investigated the potential effects of sediment load on Manning's *n* in a flume with a fixed bed, under wide ranges of hydraulics and sediment loads. Results show that Manning's *n* decreased with increment in Reynolds number and Froude number. The relationships developed are shown in Table 2.3. Manning's *n* can be predicted by using the following relationship for sediment-laden flow with coefficient of determination, $R^2 = 0.834$:

$$n = 0.003q^{-0.716}c^{0.284} \tag{2.22}$$

where q is unit flow discharge (m^2/s) and c is sediment concentration (kg/m^3).

The variation of resistance coefficients in meandering channel was investigated by Nayak et al. (2009). In their study, the influence of slope, sinuosity and geometry was investigated. Manning's *n* is found to decrease with increase of aspect ratio (*B/Y*) (ratio of width of the channel to the depth of flow). This is different with the finding by Diaz (2005) and Chang et al. (2010). Steeper slope and higher sinuosity has higher Manning's *n*.

It is a common method of relating Manning's *n* with product of velocity and hydraulic radius *VR* in predicting the value of Manning's *n* in vegetated channels. This relationship was first drawn by Palmer in 1945 (Ree & Palmer, 1949) and recorded by United States Department of Agriculture as the principle of planning vegetated channels (Chen et al., 2009). Chow (1959) stated that the relationship of hydraulic radius (*VR*) is characteristic of the vegetation and practically independent of channel slope and shape. Table consisting five different degrees of retardance: very high, high, moderate, low, and very low to describe hydraulic radius (*VR*) was detailed by Chow (1959). A modified *n-VR* curve was presented by Tsihrintzis & Madiedo (2000), appropriate for marsh preliminary hydraulic analyses and design. It is observed that Manning's *n* decrease with increasing *VR* and this was observed in the study done by Bakry (1992). However, hydraulic radius (*VR*) does not uniquely specify a flow condition and *n-VR* relationship in not independent of slope. Chen et al. (2009) addressed that hydraulic radius (*VR*) is not the best parameter in calculating the retardance coefficient in a complex flow pattern such as that for a natural stream or wetland. Apart from this, Wilson (2007) stated that *n-VR* method tends to under predict the Manning's *n*.

In realizing the limitations of using *n-VR* in estimating the value of Manning's *n*, a new method was established by using the relationship between Manning's *n* with Froude number *Fr*. Diaz (2005) and Chen et al. (2009) had drawn a good correlation between Manning's *n* and Froude number in their studies. Diaz (2005) proposed two *n-Fr* curves in estimating Manning's *n* for slope more than 20% and slope less than 20%. Chen et al. (2009) replaced *n-VR* curve in estimating Manning's *n* with *n-Fr* curves. In their studies, it is observed that retardance coefficient and Froude number are exponentially related. Manning's *n* was observed to decrease with increase in Froude number in both of the study. A summary of the relationships drawn between Manning's *n* with hydraulic parameters is detailed in Table 2.3.

Table 2.3: Relationships drawn between Manning's *n* with hydraulic parameters

Equation	Manning's *n* Equation	Condition	Coefficient of Determination, R^2	Reference
2.23	$n = 1.030Re^{-0.395}$	11 rills throughout the eastern United States	0.6030	Gilley et al., 1990
2.24	$n = 0.016V^{-0.88}$	Egyptian canals of the 1st order with discharges	0.7300	Bakry, 1992
2.25	$n = 0.004V^{-1.292}$	Egyptian canals of the 2nd order with discharges	0.8700	
2.26	$n = 0.032VR^{-0.552}$	Type one distribution	0.7400	
2.27	$n = 0.043VR^{-0.495}$	Type two distribution	0.7900	
2.28	$n = 0.037VR^{-0.523}$	Type three distribution	0.7100	
2.29	$n = 0.068Fr^{-0.958}$	Vegetated river beds with bed slopes < 20%	0.9747	Diaz, 2005
2.30	$n = 0.099Fr^{-1.009}$	Vegetated river beds with bed slopes >20%	0.9868	
2.31	$n = 0.020V^{-0.975}$	Vegetated with *E.densa* Planch	0.9900	Chen et al., 2009
2.32	$n = 0.003Q^{-0.848}$		NA	
2.33	$n = 0.012Fr^{-1.028}$		0.9900	
2.34	$n = 0.022V^{-0.804}$	Vegetated with *O.javanica*	0.7400	
2.35	$n = 0.006Q^{-0.678}$		NA	
2.36	$n = 0.013Fr^{-0.879}$		0.7100	
2.37	$n = 0.096 – 0.160V$	Non-vegetated channel	0.8600	
2.38	$n = 0.095 – 1.612Q$		NA	
2.39	$n = 0.097 – 0.252Fr$		NA	
2.40	$n = 0.028Re^{-0.084}$	Sediment-free flow	0.3080	Zhang et al., 2010
2.41	$n = 0.448Re^{-0.408}$	Sediment-laden flow	0.7120	
2.42	$n = 0.015Fr^{-0.012}$	Sediment-free flow	0.0100	
2.43	$n = 0.042Fr^{-0.730}$	Sediment-laden flow	0.5460	

Note: NA denotes not available

2.5 Review of Grassed Swale and Subsurface Drainage System

Grassed swales, also known as infiltration swales, biofilters, bioswales, vegetated swales, or in-line bioretention, are vegetated open channels specifically