SELF-CLEANSING URBAN DRAIN USING SEDIMENT FLUSHING GATE BASED ON INCIPIENT MOTION

by

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TABLE OF CONTENT

CHAPTER 3 METHODOLOGY

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	flow area [m^2]
A_d	total cross sectional area of the drain [m^2]
A_H	outflow area through orifice [m^2]
A_I	total impervious area [km^2]
A_s	cross sectional area occupied by sediment deposit [m^2]
A_T	total catchment area for drain [km^2]
B	channel bed width [m]
B^*	bimodality parameter
B_{Wup}	upper weir width [m]
b	lower weir width [m]
C_p	Mallows' goodness-of-prediction
C_v	volumetric sediment concentration [ppm]
D	pipe diameter/channel depth [m]
D_{gr}	dimensionless grain diameter
$D.R.$	discrepancy ratio
d	particle size [m]
d_{50}	particle median diameter size [m]
d_m	particle mean diameter size [m]
d_{md}	particle mode diameter size [m]
F_D	drag force [N]
F_d	particle Froude number

F_h	hydrostatic force over the cross section [N]
F_L	lift force [N]
F_R	resistance force [N]
Fr	Froude number
F_ω	force due to channel width variations [N/m]
g	acceleration due to gravity [m^2/s]
h	upstream water level [m]
h_{bar}	barycentre of outflow area from channel bottom [m]
h_{Wlow}	lower weir height [m]
h_{Wup}	height of crest of upper weir [m]
I	Shvidchenko and Pender (2000) intensity of motion [s^{-1}]
k	number of terms in the model plus the intercept
L	length [m]
L_s	mean sediment bed front advancement from initial position [m]
M_O	overturning moment [Nm]
M_R	resisting moment [Nm]
m	number of particle displaced over an area
N	Neill and Yalin (1969) incipient motion dimensionless parameter
n	number of observation / number of flush
n_p	number of particle available in an area
$\dot{n}^n$	number of grain displaced per unit area of bed per unit time
p	number of terms in the model
Q	discharge [m^3/s]

Q_H	outflow through lower orifice [m^3/s]
Q_s	sediment discharge [m^3/s]
Q_{Wlow}	outflow through lower weir [m^3/s]
Q_{Wup}	outflow over upper weir [m^3/s]
R	hydraulic radius
Re	Reynolds number
Re_*	grain Reynolds number
R_p^2	coefficient of determination for regression model
R_{adj}^2	adjusted coefficient of determination for regression model
r	correlation coefficient
S_0	channel slope
S_f	energy grade slope line
S_s	sediment specific gravity
T	Temperature [°C]
t_s	sediment deposition thickness [m]
V	average velocity [m]
V_c	critical velocity [m/s]
V_L	self-cleansing velocity [m/s]
V_s	scour velocity [m/s]
V_t	threshold velocity [m/s]
W	width [m]
W_i^*	reference transport criterion
W_s	fall velocity [m/s]

y	flow depth [m]
y_0	normal flow depth [m]
ϕ	particle size in phi unit
ϕ_0	angle of repose of particle
γ_g	specific weight of gate [N/m^2]
γ_w	specific weight of water [N/m^2]
λ_0	Darcy-Weisbach friction factor
μ	mean value
μ_H	discharge coefficient of lower orifice under head
μ_{Wlow}	discharge coefficient of lower weir
μ_{Wup}	discharge coefficient of upper weir
θ	angle of gate opening from the horizontal axis [°]
θ_c	dimensionless critical shear stress
θ_s	dimensionless shear stress
ρ	density of fluid [kg/m^3]
ρ_s	density of particle [kg/m^3]
σ	standard deviation
σ_g	geometric standard deviation
τ	mean bed shear stress [N/m^2]
τ_c	critical shear stress [N/m^2]
τ_i^*	dimensionless Shields shear stress for i th size fraction
τ_{ri}^*	reference Shields shear stress
υ	kinematic viscosity of fluid [m^2/s]

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ARI	Annual Recurrence Interval
ASTM	American Society for Testing and Materials
BC	Bau Commercial
BDCC	BDC Commercial
BDCR	BDC Residential
BLC	Bayan Lepas Commercial
BLI	Bayan Lepas Industrial
BLR	Bayan Lepas Residential
BoC	Bormill Commercial
BR	Bau Residential
BS	British Standard
BW	Bottom Width
CCTV	Closed-Circuit Television
CIRIA	Construction Industry Research and Information Association, UK
CPC	Central Park Commercial
DID	Department of Drainage and Irrigation, Malaysia
FPA	Fixed Point Average
GHR	Green Height Residential
HSGR	Hui Sing Garden Residential
IDF	Intensity – Duration – Frequency
JSR	Jalan Song Residential
KSC	Kota Samarahan Commercial

KSR	Kota Samarahan Residential
LHS	Left Hand Side
MMC	Mak Mandin Commercial
MMI	Mak Mandin Industrial
MMR	Mak Mandin Residential
MPM	Meyer-Peter and Muller
MPSP	Majlis Perbandaran Seberang Perai
MSE	Mean Square Error
NTC	Nibong Tebal Commercial
NTR	Nibong Tebal Residential
PerI	Perai Industrial
PI	Pending Industrial
REDAC	River Engineering and Urban Drainage Research Centre
RHC	RH Plaza Commercial
RHS	Right Hand Side
SC	Serian Commercial
SR	Serian Residential
SSE	Sum of Square Error
SST	Sum of Square Total
TJC	Tabuan Jaya Commercial
TVD	Total Variation Diminishing
TW	Top Width
UK	United Kingdom

SALIRAN BANDARAN CUCI DIRI DENGAN PENGGUNAAN PINTU SIMBAH MENDAPAN BERDASARKAN PERGERAKAN AMBANG

ABSTRAK

Mendapan di dalam saliran bandaran air ribut konkrit terbuka telah menyebabkan banyak masalah seperti banjir kilat dan pencemaran alam sekitar. Kajian ini bertujuan untuk memberi cadangan untuk mengurangkan pemendapan dalam saliran bandaran air ribut konkrit terbuka. Untuk memahami ciri-ciri fizikal pemendapan, pensampelan telah dilakukan dari 57 lokasi di bandar Kuching, kawasan bandar sekitar bandar Kuching dan juga Pulau Pinang. Sampel-sampel tersebut diambil dari kawasan kediaman, komersil dan juga industri untuk tujuan analisis ayakan. Keputusan ayakan telah menunjukkan kebanyakan sampel adalah bukan organik dan tidak jeleket. Kandungan sampel tersebut mengandungi pasir sebagai komponen utama; diikuti kelikir, tanah liat serta kelodak. Untuk mendapatkan kriteria reka bentuk yang lebih baik, eksperimen pergerakan ambang telah dijalankan di dalam flum dengan kelebaran 0.6 m menggunakan pasir dengan saiz d_{50} 0.81 mm, 1.53 mm dan 4.78 mm. Dengan menggabungkan keputusan eksperimen pergerakan ambang tersebut dengan hasil penyelidik terdahulu yang menggunakan flum dengan kelebaran 0.3 m, regresi linear berganda telah dilakukan untuk mendapatkan persamaan yang terbaik bagi pendekatan tegasan ricih kritikal dan juga pendekatan halaju kritikal. Satu carta reka bentuk cuci diri yang menghubungkan kecerunan minimum saliran dengan kadar alir reka bentuk minimum untuk saiz saliran piawai juga dicadangkan. Untuk meningkatkan lagi keupayaan cuci diri dalam saliran air ribut konkrit terbuka, pintu simbah telah direka dan dipasang di dalam saliran air ribut konkrit terbuka di Taman Pekaka, Nibong Tebal, Pulau Pinang. Pemantauan pintu simbah tersebut telah dilakukan selama empat bulan dari 14 November 2012 hingga 15 Mac 2013. Keputusan menunjukkan pintu simbah tersebut berkesan dalam mengurangkan jumlah isipadu mendapan yang terkumpul secara semulajadi di dalam saliran air ribut tersebut. Eksperimen untuk menentukan ciri-ciri pintu simbah dan juga prestasi simbahan telah dijalankan di dalam makmal menggunakan dua flum yang mempunyai dimensi berbeza. Hasil eksperimen daripada flum pertama menunjukkan bahawa sudut bukaan pintu simbah dan masa operasi simbahan mempunyai kesan ke atas prestasi simbahan dan sudut bukaan pintu simbah mempunyai kesan yang lebih ketara dibandingkan dengan masa operasi simbahan. Eksperimen di dalam flum kedua secara amnya menunjukkan bahawa bilangan simbahan yang diperlukan untuk membersihkan mendapan pasir sejauh 1 m dari tempat asal mendapan tersebut diletak meningkat secara purata dua kali apabila ketebalan mendapan pasir ditingkatkan dengan dua kali ganda. Satu persamaan yang mengaitkan bilangan simbahan yang diperlukan dengan sudut bukaan pintu simbah dan ketebalan mendapan telah diterbitkan. Garis panduan untuk reka bentuk dan pemasangan pintu simbah di dalam saliran air ribut konkrit terbuka juga dicadangkan.

SELF-CLEANSING URBAN DRAIN USING SEDIMENT FLUSHING GATE BASED ON INCIPIENT MOTION

ABSTRACT

Sediment deposition in urban open concrete storm drain has caused many adverse effects to the drainage system such as flash flood and environmental pollution. This study aimed to provide recommendations for the purpose of sedimentation mitigation in urban open concrete storm drain. To understand the physical characteristics of sediment deposition; sampling was taken from 57 locations in Kuching city, surrounding towns outside Kuching city and Penang consisting of residential, commercial and industrial areas and subjected to sieve analysis. Results showed that the samples were mainly inorganic and non-cohesive with sand as the major component followed by gravel and silt and clay for most of the samples. To improve the design criteria, incipient motion experiments were conducted in a 0.6 m wide flume for sediment with d_{50} sizes of 0.81 mm, 1.53 mm 4.78 mm. Combining the results from the current incipient motion experiments with the results from an earlier researcher for a 0.3 m wide flume, multiple linear regression were performed and the best equations for each of the critical shear stress and critical velocity approach were developed. A design chart relating the self-cleansing design relationship between drain minimum slope with the design minimum flow rate and the respective standard drain size was also developed. To further improve the self-cleansing capability of open concrete storm drain, a tipping flush gate was designed and installed on site at Taman Pekaka, Nibong Tebal, Penang and subjected to monitoring for four months between 14th November 2012 and 15th March 2013. Results showed that the tipping flush gate was effective in reducing the total volume of naturally accumulated sediment in the monitored drain section. Experiments on the gate characteristics and flushing performance were conducted in the laboratory with two flumes of different dimensions. Results from the first flume showed that both the gate opening angle and duration of flushing have effect on the flushing performance with the gate opening angle slightly more significant. Experiments in the second flume generally showed that the number of flushes required to totally remove the sediment bed from the 1 m where the bed was initially laid increased by an average of two times as the sediment bed thickness doubled. An equation relating the number of flushes required with the angle of gate opening and sediment deposition thickness was developed. Guidelines on the design and installation of tipping flush gate on site have also been presented.

CHAPTER 1
INTRODUCTION

1.1 Background

Open concrete drain systems are frequently used in developing (Geiger, 1990) and less developed countries to convey storm water runoff. Though closed conduits are more hygienic and aesthetic; the construction and maintenance of closed conduits are more costly than open channels and need special equipment or trained staff. Due to this, open channels are still favoured in spite of the benefits of closed conduits. Open concrete storm drain system could be quite efficient in rapid removal of surface runoff; however, sediment deposition tends to build up in the drain after a period of time (Figure 1.1). Sediment deposition in urban open concrete storm drains had caused many adverse effect to the drainage system itself such as reduction in hydraulic capacity (which had been identified as one of the cause of flash flood) and environmental pollution due to the high pollutant concentrations that might be released during the erosion of these deposition (Ashley et al., 1992a; Schellart et al., 2010; Rodríguez et al., 2012).

Generally, only limited data and works were available in the literature for sediment in storm drain for developing and less developed countries as compares to European countries (Ashley et al., 2004). Though some data on sediment for developing countries exist in unpublished literature such as consulting reports; these data are difficult to obtain, the measurement procedures are not always known and the variability from one study to another is great (Ashley et al., 2004). Hence is still a lack of understanding of the sediment properties commonly found in urban open drain especially in developing and less developed countries.

Figure 1.1: Sediment deposition in open concrete drain

To reduce sediment deposition, open drain has been designed to have self-cleansing properties. Many designers prefer to use the adoption of a single minimum constant value of velocity or shear stress since these criteria are easier to use, especially for a simple or small drainage system and sewer network. In Malaysia, to prevent sedimentation in lined open drain; a minimum average flow velocity of not less than 0.6 m/s has been recommended in “Urban Stormwater Management Manual for Malaysia” (DID, 2000) which was replaced later by “Urban Stormwater Management Manual for Malaysia – 2nd Edition” (DID, 2012). Older design manual, namely “Planning and Design Procedures No.1: Urban Drainage Design Standards and Procedures for Peninsular Malaysia” (DID, 1975) had recommended a minimum velocity of 0.9 m/s. The adoption of a minimum constant velocity might have shown some success; however the disadvantage is it does not properly taken into account the characteristics and concentration of sediment and also the hydraulic aspects of the drain (Butler et al., 2003; Vongvisessomjai et al., 2010; Campisano et al., 2013).

Thus, instead of using directly a minimum velocity or shear stress directly from design manual, a more viable approach for self-cleansing design is through the use of incipient motion equations which incorporate some aspect of the sediment and channel characteristics. For this purpose, the Shields diagram (Shields, 1936) was widely used to predict incipient motion of granular particles especially for loose boundary channel such as alluvial channel (Vongvisessomjai et al., 2010). However, the boundary conditions found in sewers and storm drain which are of rigid boundary could be quite different (Ashley et al., 2004). For a rigid boundary channel, there is a limitation in terms of depth of sediment and source of new sediment for transport (Butler et al., 1996a). Study by Novak and Nalluri (1975) on rigid smooth bed channels has shown that the incipient motion value was substantially lower than for loose boundary channels for any particle size. Nevertheless, since majority of the literature on incipient motion was on loose boundary channel than rigid boundary channel (Novak and Nalluri, 1984); the Shields diagram has been applied in a number of studies on sewer and storm sewer (Laplace et al., 1992; Verbanck et al., 1994; Almedeij, 2012) despite the difference in boundary conditions.

For most developing and less developed countries, removal of sediments from open storm drains often involves manual handling which is costly (see Figure 1.2). In European countries, besides designing for self-cleansing, various techniques have been developed to aid in removal of sediment deposition in sewer system. Of the various techniques; the one based on hydraulic effects mainly consist of creating a flushing effect by discharging a volume of water during a short period of time. The flushing effect could be created by storing water in upstream chambers and discharged through a gate, tipping bucket located above water level or mobile tipping plates like Hydrass gate (Chebbo et al., 1996; Lorenzen et al., 1996). These devices allow production of successive flushing waves to scour and transport sediments and represent an automated cost-effective solution for sewer cleansing. Experimental studies on the scouring effect and numerical analysis had been carried out to understand the operation of flushing gates (Campisano et al., 2004; Guo et al., 2004; Bertrand-Krajewski et al., 2005). Long term monitoring of sewer sediment to study the effectiveness of flushing gate had also been done (Bertrand-Krajewski et al., 2006). Though various literatures exist on flushing devices for sewer or combined sewer systems, it is still a new concept yet to be tested for open storm drain especially for developing and less developed countries.

Figure 1.2: Removing sediment deposition in open concrete storm drain manually

1.2 Problem Statement

Sediment deposition in urban open storm drain is a serious problem especially in highly populated urbanised area due to negative effects that it might caused such as flash flooding (due to reduction of channel carrying capacity) and pollution from the pollutant existed in the sediment. However, only limited data on sediment and its characteristics in storm drain for developing and less developed countries could be found in the literature. For many years, urban open concrete storm drains have been designed so as to have self-cleansing properties by adopting a single recommended minimum velocity or shear stress values or by using incipient motion criteria. Yet, the adoption of a minimum constant velocity or shear stress does not properly take into account the characteristics and concentration of sediment and also the hydraulic aspects of the drain. Thus sedimentation in concrete drains still remains as a problem and frequent manual sweeping and cleaning of open concrete drain is required. This study aimed to provide recommendations for the purpose of sedimentation mitigation in urban open concrete storm drain. This was done through determining the characteristics of sediment commonly found in Malaysian open concrete drain; development of incipient motion equations and design chart for self-cleansing criteria and testing the feasibility and ability of sediment removal using tipping flush gate.

1.3 Objectives of Study

The objectives of this study are as follows:

a) To establish the typical physical characteristics of sediments in urban areas.
b) To establish the incipient motion (initiation of motion) characteristics for different size sediment, sediment thickness and channel slopes under uniform flow conditions for the development of self-cleansing design criteria for open drains.
c) To identify the significant characteristic parameters for critical shear stress and critical velocity equations.
d) To design a tipping flush gate capable of removing deposited sediment for use in urban drains.

1.4 Scope of Study

The field data collection to determine the physical characteristics of sediment was limited to the urban areas in Kuching city, towns surrounding Kuching city (Kota Samarahan, Bau and Serian) and Penang (both the island and mainland). Samplings were done for residential, commercial and industrial areas in those locations. As for the establishment of incipient motion characteristics, the experimental work was limited to a rectangular flume with dimensions of 6.3 m (L) x 0.6 m (W) x 0.4 m (D) which is already available in the Physical Modelling Laboratory of River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia (Engineering Campus). The sediment samples used for the experimental work consisted of three different mixtures namely; Mixture 1 (uniform sand with d_{50}=0.81 mm); Mixture 2 (slightly non-uniform mixture of sand and gravel with d_{50}=1.53 mm) and Mixture 3 (uniform gravel with d_{50} = 4.78 mm) with four different thickness ($t_s = d_{50}$, 5 mm, 10 mm and 24 mm) and four differing slopes of the channel (0.005, 0.00286, 0.002 and 0.001). Another set of incipient motion data was obtained from the work by Salem (1998). To test the capability of removing deposited sediment in urban drains, a tipping flush gate was designed and installed in a selected site in Taman Pekaka, Nibong Tebal, Penang and monitored for four months. Models of the self automated tipping flush gate were also tested in two experimental flumes. The first flume with dimensions of 11.0 m (L) x 1.2 m (W) x 0.8 m (D) was used to test and simulate as close as possible the condition and operation of the gate on site in terms of opening duration and also the effect of gate opening angle on the changes of sediment bed profile. For the second flume with the dimensions of 6.30 m (L) x 0.60 m (W) x 0.49 m (D), a scale down of 1:2 model of the gate opening dimensions for the tipping flush gate used on site was installed in the flume to determine the effect of sediment size, angle of gate opening, sediment thickness and distance of sediment from the gate on the flushing ability.

1.5 Structure of Thesis

This thesis is divided into 7 chapters. Chapter 1 gives brief introduction and discussion on the issue of sediment deposition in open concrete drains, the current trend in sediment deposition management, the objectives and scope of study. Chapter 2 gives reviews from the literature on the source of sediment, classification of sediment, sediment characteristics in sewer and storm drain. A review from the literature of existing study on incipient motion and flushing devices for sediment control are also included in Chapter 2. Chapter 3 gives the methodology used in the current study and basically divided into three parts, namely the sampling of sediment from urban open concrete storm drain, incipient motion experiment and tipping flush gate experiments for both site monitoring and laboratory. Chapter 4 presents the results in terms of the physical characteristics from the sediment sample collection from 57 locations for the current study. Chapter 5 presents the results from the incipient motion experiment and also the development of critical shear stress and critical velocity equations from the data of the current study. Design chart for the purpose of self-cleansing design of open concrete drain is also presented in Chapter 5. Chapter 6 presents the results from tipping flush gate experiments for both the site monitoring and also experimental work in laboratory. Design guidelines on installation of tipping flush gate on site are also given in Chapter 6. Chapter 7 presents the important findings from the current study and also research outlook for the future.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Sediment deposits in urban open concrete storm drains had been known to have adverse effects on the hydraulic performance of the system and also on the environment. Losses of hydraulic capacity due to sediment deposition have been identified as one of the factors of flash flooding in urban areas (Ab. Ghani et al., 2008; Liew et al., 2012; Rodríguez et al., 2012). Sediments originate from rooftops, streets and highways, construction sites, commercial and industrial parking lots and runoff (Fan et al., 2003). Sediment deposition could be because of structural causes due to design where deposits will probably occur at certain locations and accidental causes due to entry into networks of various foreign objects (Chebbo et al., 1996). Traditionally sediment deposits were removed manually and could be costly due to the periodic maintenance (Pisano et al., 2003; Lange and Wichern, 2013).

Design of urban open drains according to self-cleansing criteria and the use of recent techniques based on hydraulic devices such as what have been done in European countries for their sewer system might be able to reduce sediment deposition. However, the commonly used self-cleansing approach in terms of a constant minimum critical shear stress (τ_c) or critical velocity (V_c), could not properly represent the ability of drain flows to transport sediment due to non-relational of the constant value to the characteristics of the sediment or to other aspects of the hydraulic behaviour of the drain (Butler et al., 2003). The determination of critical shear stress (τ_c) or critical velocity (V_c) through incipient motion criteria might be a more viable approach since most of the incipient motions criteria in the literature incorporated some aspects of the sediment and drain characteristics. However, most of the available incipient motion criteria available in the literature were for loose boundary channel which is very different with the boundary conditions found in open concrete drain which is of rigid boundary. Despite the difference in boundary condition, findings of incipient motion from loose boundary studies (such as the Shields diagram) are widely used in the study and design of sewer and storm drain (Ashley et al., 2004).

The use of hydraulics devices such as flushing gates have been found to be able to further reduce sediment deposition in sewers in European countries beside designing the sewer according to self-cleansing criteria. Conversely, the literature is still lacking on the usage of these devices in open drain. Thus, studies are needed to test the feasibility of these devices to be used for sediment removal and also the problems that might be faced by installing such devices in open drain.

2.2 Sediment

Sediment can be defined as any settleable particulate material which is able to form bed deposits in the drainage/sewerage system (Butler et al., 1996a). In storm sewers, sediments are mainly inorganic and non-cohesive; while sediments in sanitary sewers have cohesive like properties (Butler et al., 2003). In combined sewers, the sediments tend to be a combination of the two types.

2.2.1 Source of Sediment and Deposition

The main sources of sediment in urban drainage had been identified as from the atmosphere, the surface of the catchment, domestic sewerage, industrial and commercial effluents and solids from construction site (Tranckner et al., 2008). Ab.

Ghani et al. (2001) carried out sediment samplings in drainage systems of five cities in Malaysia and has noted that the main source of sediments are mainly from ingress of surrounding areas, construction works, road surfacing materials and road works (see Figure 2.1).

Several factors had been identified to have effects on sediment transport and thus its deposition such as sediment characteristics (size, sediment concentration) and drain characteristics (size, slope and roughness) (Ab. Ghani et al., 2000). A preliminary study at Sungai Raja drainage system in Alor Setar, Kedah, Malaysia has established the effect of larger sediment deposition volume occurs with mild slopes and small drain capacity (Ab. Ghani et al., 2001). Other factors that might affect sediment deposition are tidal effect, litter, drain alignment and size uniformity (Ab. Ghani et al., 2000).

Figure 2.1: Sand and aggregates from road surface material accumulating by the roadside which will be washed into roadside open drain when rains

2.2.2 Sediment Classification

The nature of combined sewer sediments was first defined systematically by Crabtree (1989). For combined sewers, it is widely accepted to have cohesive properties due to the presence of organic substances (Campisano et al., 2008). Initial observations of the nature and appearance of combined sewer sediments during sampling and prior to the availability of the analytical results suggested five distinguished categories of sediment deposit (Crabtree, 1989). These categories were based on observations of the provenance, nature and location of deposits within the sewerage system as summarised in Table 2.1.

Table 2.1: Categories of sediment deposit (Crabtree, 1989)

Type	Characteristics
A	coarse, loose, granular, predominantly mineral, material found in the inverts of pipes
B	as Type A but concreted by the addition of fat, bitumen, cement, etc. into a solid mass
C	mobile, fine grained deposits found in slack flow zones, either in isolation or above Type A material
D	organic pipe wall slimes and zoogloeal biofilms around the mean flow level
E	fine-grained mineral and organic deposits found in SSO storage tanks

For storm sewers, it is mainly inorganic and non-cohesive (Butler et al., 2003). Thus the classification system used in this thesis for non-cohesive sediment particle size commonly found in urban open storm drain is based on BS 5930:1999. Table 2.2 shows the soil classification system based on BS 5930:1999.

Table 2.2: Soil classification based on BS 5930:1999
(modified from British Standard Institution (1999))

Basic soil type	Particle size (mm)
Boulders	>200
Cobbles	60 – 200
Gravel	2 – 60
Sand	0.06 – 2
Silt and clay	<0.06

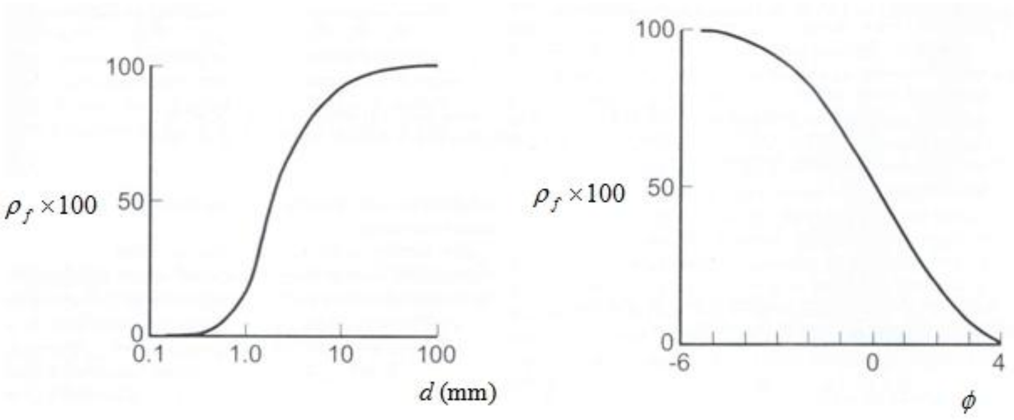
2.2.3 Sediment Size Distribution

Sediment sample normally contains a range of sizes. Thus, a grain size distribution is an appropriate way to characterize these samples. The conventional engineering representation of grain size distribution consists of a plot of $\rho_f \times 100$ (percent finer) versus $\log_{10}(d)$ where a semilogarithmic plot is employed (see Figure 2.2 (a)). The same distribution when plotted in sedimentological form involving plotting $\rho_f \times 100$ versus ϕ on linear plot would look like the one in Figure 2.2 (b). In sedimentological scale, ϕ is related to grain size diameter d by the following equation:

$$\phi = -\frac{1}{\log_{10}(2)}\log_{10}(d) \tag{2.1}$$

It follows that the corresponding grain size in terms of equivalent diameter is given by d_x, where;

$$d_x = 2^{-\phi_x} \tag{2.2}$$



(a) (b)

Figure 2.2: Sediment grain size distribution in (a) semilog scale, and
(b) sedimentological scale ϕ (Garcia, 2008)

The value of median diameter d_{50} was estimated from the grain size distribution. Median diameter d_{50} is the size with a 50% passing on the grain distribution curve while mode d_{md} is the size having the largest percentage retained. The mean diameter d_m for the sample was calculated using the following expression:

$$d_m = \frac{\sum \Delta_i d_i}{100} \tag{2.3}$$

where Δ_i represents any portion of the percentages shown on the vertical axis of the cumulative grain size distribution curve and d_i represents the mean value of the sizes established by the extreme values of the interval Δ_i. The standard deviation σ is given by:

$$\sigma = \left[\frac{\sum_{i=1}^{j} f_i (d_i - d_m)^2}{\sum_{i=1}^{j} f_i} \right]^{1/2} \tag{2.4}$$

where d_i is the mean size of i th class; d_m is the mean size of the sample (see (2.3)); f_i is the percentage of sample by weight of i th class and j is the total number of classes (Almedeij et al., 2010). The geometric standard deviation σ_g is given by:

$$\sigma_g = 2^{\sigma} \tag{2.5}$$

For a perfectly uniform material, $\sigma = 0$ and $\sigma_g = 1$. For practicality, a sediment mixture with σ_g value less than 1.3 is often considered as well-sorted and treated as uniform material. When σ_g values exceed 1.6, the material is considered as poorly-sorted (Garcia, 2008).

For samples displaying bimodality characteristics (having 2 modes), the degree of bimodality could be quantified according to the criterion proposed by Smith et al. (1997). The bimodality degree criterion is determined from:

$$B* = |\phi_2 - \phi_1| \left(f_{md2} / f_{md1} \right) \tag{2.6}$$

where $B*$ is the bimodality parameter; ϕ is mode grain size in phi units where $\phi = \log_2 d_{md}$ and d_{md} is the mode size. The subscript 1 and 2 denotes the primary and secondary modes in terms of sediment proportion of sample by weight respectively. However, if the two modes are exactly equal values, then subscript 1 refers to the coarser one. A reference value suggested by this criterion is $B^* = 1.7$ (Smith et al., 1997). Any sample with bimodality parameter value above 1.7 is considered to be bimodal where bimodality characteristic is effective. A sample with value below 1.7 is considered as unimodal and would behave as if a unimodal material.

2.2.4 Sediment Characteristics in Urban Areas

Ab. Ghani (1997) had given a review of field data study in European countries on sediment deposition in both separate and combined sewerage system (see Table 2.3). Sediment samplings in drainage systems of five cities in Malaysia namely Alor Setar, Butterworth, Ipoh, Kota Bharu and Johor Bahru had been carried out by Ab. Ghani et al. (2000) and as shown in Table 2.4. A comparison between the drain sediment size distribution from developing countries like India (Kolsky, 1998) and Malaysia (Ab. Ghani et al., 2000) with European data has shown that sediment in India are considerably coarser than those found in Malaysia and European countries (Ashley et al., 2004). The sediment data from Malaysia though slightly coarser than the European data, shows greater similarity to European sediment due to dumping of refuse in open storm drains is almost non-existent in Malaysia as compares to India (Ashley et al., 2004).

The results from the sediment sampling in drainage systems in five cities in Malaysia had generally shown that for each sample, more than 90% of the constituents are in the range of sand and gravel (Ab. Ghani et al., 2000). Sand was the major components in most of the samples with the average values for the five cities ranging from 61.8% to 87.6%. Gravel had an average values ranging from 12.2% to 32.0% for the five cities while silt and clay had an average value of 0.0% to 6.2%. The median size d_{50} for the five cities had an average value ranging from 0.6 mm to 0.9 mm (Ab. Ghani et al., 2000). Further sediment sampling in drainage system for major cities in Malaysia was done by Kassim (2005) as shown in Figure 2.3. The median size d_{50} for the sediment from the major cities in Malaysia ranged from 0.35 mm to 2.40 mm with an average value of 0.75 mm (Kassim, 2005). Comparing the results for five cities in Malaysia (Ab. Ghani et al., 2000) and major cities in Malaysia (Kassim, 2005) with a more recent study for 5 residential areas in Kuwait; the results from Kuwait had shown that the sediment median size d_{50} were smaller ranging from 0.13 mm to 0.52 mm for the unimodal (one mode samples) (Almedeij et al., 2010).

Table 2.3: Sediment characteristics in sewers (Ab. Ghani, 1997)

Researcher	Particle size (mm)	Specific gravity	Volumetric concentration (ppm)
Verbanck (1992)	0.20 – 0.50	n/a	n/a
Laplace et al. (1992)	0.30 – 3.00	n/a	25
Ashley et al. (1992)	0.10 – 0.50	n/a	n/a
CIRIA (1987)	0.10 – 9.00	n/a	n/a
Urcikan (1984)	0.34 – 2.94	n/a	n/a
Broeker (1984)	n/a	2.45	n/a
Macke (1983)	0.06 – 2.00	n/a	n/a
May (1982)	2.50	n/a	20
Mittelsdadt (1979)	n/a	n/a	7 - 110

Table 2.4: Sediment characteristics in Malaysian drainage system (Ab. Ghani et al., 2000)

City	Development type	Mean sediment size d_m (mm)
Alor Setar	Commercial	0.6 – 2.9
Butterworth	Industrial	0.6 – 1.8
Ipoh	Commercial	0.8 – 1.5
Kota Bharu	Housing scheme	0.1 – 2.4
Johor Bahru	Housing scheme	0.5 – 0.7

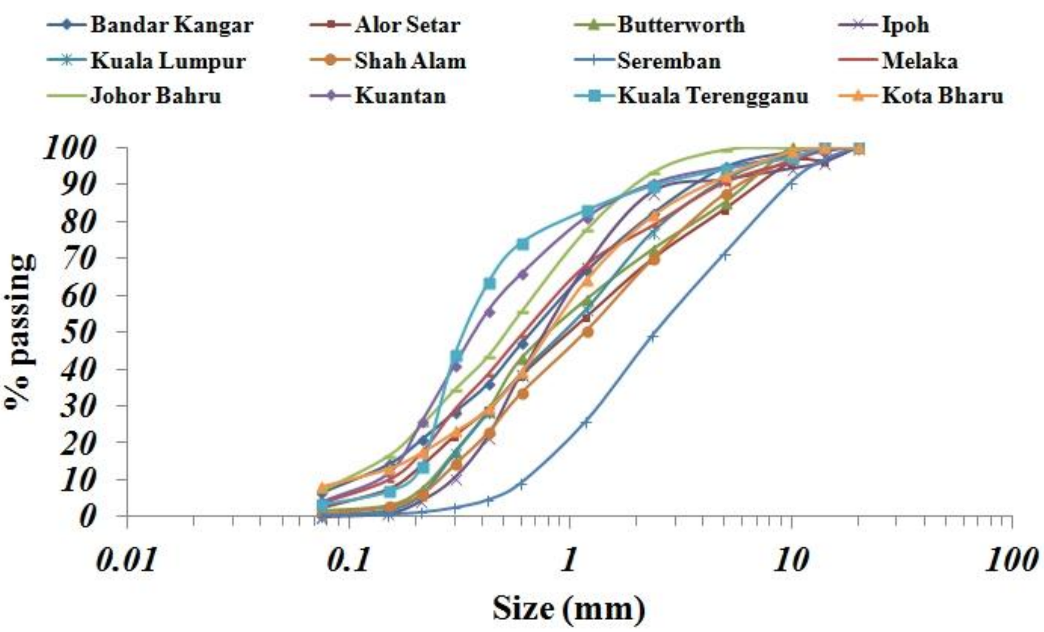


Figure 2.3: Sediment size distribution for major cities in Malaysia (Kassim, 2005)

A study on sediment size distribution characteristics in Hamilton Canada (Vermette et al., 1987) found relationship between mean sediment size with traffic characteristics and land use. Samples with small mean particle sizes and large standard deviations were taken from parking lots in commercial areas and industrial areas. These areas experience high traffic volumes that gradually pulverize the aggregates and increase the percentage of finer material, though some of the larger material still present, thereby increasing the dispersion value. Samples from high traffic volume and high traffic speed areas such as commercial areas also exhibit greater positive skewness (i.e. towards the larger sizes) and smaller standard deviations than samples from lower traffic volume and lower traffic speed such as residential areas. This is due to the turbulent wind eddies generated by higher speed and traffic volume that can remove finer particles through resuspension; thereby help produce a more positive-skewed and better sorted sediment through selective transport (Vermette et al., 1987).

2.2.5 Sediment Erosion and Deposition Process

The erosion and deposition processes and characteristics of sediment in combined sewer have been well documented in the literatures for European countries where there were comprehensive studies been done on various aspects of sediments especially in Belgium (Verbanck, 1990), France (Laplace et al., 1992) and the United Kingdom (Crabtree, 1989; Ashley et al., 1990; Ashley et al., 1992a; Ashley et al., 1992b) in the late 80s and early 90s. Earlier studies in Germany have indicated that no sedimentation in sewer for average boundary shear stress exceeding 4 N/m^2 while significant deposition occurs for shear stress below 1.8 N/m^2 (Stotz and Krauth, 1984; Stotz and Krauth, 1986). Monitoring in Brussels Main Trunk Sewer have shown that the total volume of deposition was more influenced by rainfall events than human sewer-cleaning practices (Verbanck, 1990). Study in Dundee has shown no consistent pattern for erosion or deposition within the sewer lengths as a result of storm flows (Ashley et al., 1990). From the study in Marseille, rains have been found to cause sudden increase of sediment volume in trunk sewer as well as local erosion while dry weather flow grades the surface which overtime becomes steeper with deposition (Laplace et al., 1992). Further study in Dundee shown that deposition occurs during periods of dry weather and during decelerating flows when storm runoff is receding and it is apparent that bed shear about 1.8 N/m^2 is responsible for bed erosion while subsequent reduction in shear allows re-deposition (Ashley et al., 1992b). Ashley et al. (1992b) also observed that there appears to be a declining rate of deposition with time which appears to be independent with rainfall except for sudden unpredictable changes caused by particularly severe storms. The field study in Aalborg, Denmark for a sewer system has established the dry weather flow profile as well as the sediment transport processes (Schlutter and Schaarup-Jensen, 1998).

More recently, Lange and Wichern (2013) has studied the sedimentation dynamics in combined sewer systems so as to optimise the sewer cleaning intervals. It was found that as long as a state of sediment deposition equilibrium below a critical value (e.g. 15% of the pipe diameter) is reached, there is no need to clean the sewers at regular intervals of 2 years or less (Lange and Wichern, 2013).

In Malaysia, a study on the sediment deposition trend for Raja River Drainage system which is an open drain system in Alor Setar, Kedah, Malaysia for before and after rainy season has resulted in coarser sediment were found in the bed after rainy season indicating sediment erosion occur during high flow in rainy season (Ab. Ghani et al., 2008). Not much other further study could be found in the literature regarding erosion and deposition processes especially during normal daily and monthly operations or for long term monitoring of open concrete drain such as the one used in Malaysia.

2.3 Self-Cleansing Design

In the design for storm drainage system for the purpose of self-cleansing, the system must be able to transport sediment and the system is free from sediment deposit as much as possible. The Construction Industry Research and Information Association (CIRIA), UK defined self-cleansing for sewer design as “An efficient self-cleansing sewer is one having a sediment transport capacity that is sufficient to maintain balance between the amounts of deposition and erosion, with time-averaged depth of sediment deposit that minimizes the combined costs of construction, operation and maintenance” (Butler et al., 1996b; Butler et al., 2003). A search in the literature for self-cleansing design of sewer will generally categorises the design concepts into three groups namely based on non-deposition of sediment; based on moving of existing sediment on sewer bed; and based on energy slope (Vongvisessomjai et al., 2010). The design concepts in each group could be classified further into smaller groups as shown in Figure 2.4.

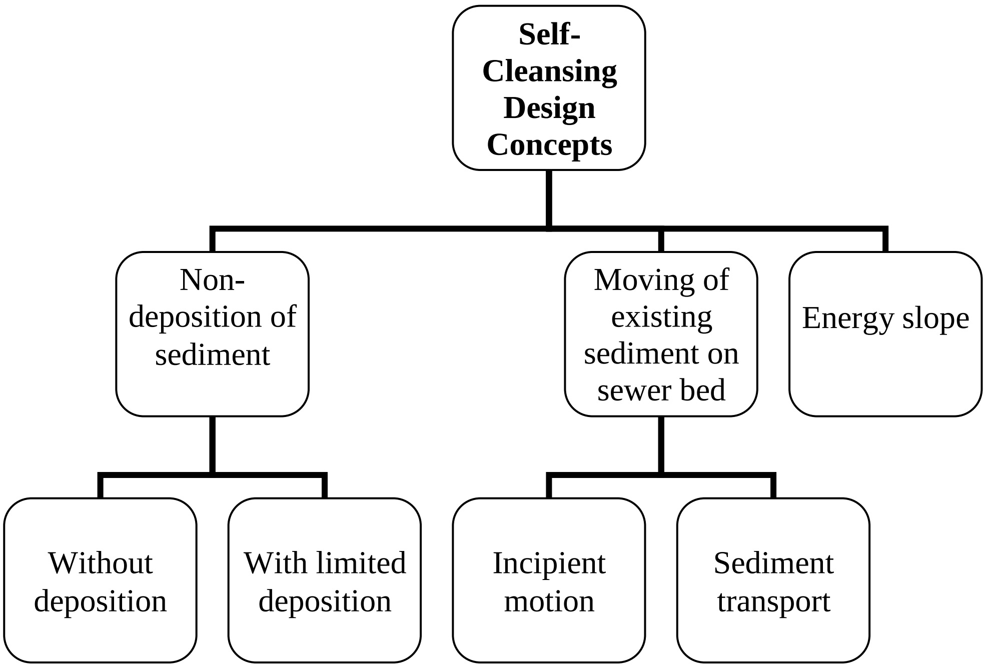


Figure 2.4: Classification of self-cleansing design concepts from the literature (modified from Vongvisessomjai et al., 2010)

2.3.1 Design Concept Based on Non-deposition of Sediment

In this design concept, conventionally the adoption of experience-based hydraulic criteria either minimum critical velocity or minimum critical shear stress is used. Minimum critical velocity V_c is the most widely used design criteria for self-cleansing (Butler et al., 1996b). In the UK, two documents relevant to sewer design advocate the use of minimum critical velocity, namely “Sewers for adoption” by Water Services Association and “BS8005:Part 1: 1987: Sewerage – guide to new sewerage construction” by British Standard Institution (Butler et al., 1996b). The British Standard; BS8005 recommended a minimum critical velocity of 0.75 m/s for storm sewer and 1.0 m/s for combined sewer. In Malaysia, the minimum average flow velocity for open lined drain shall not be less than 0.6 m/s and restricted to a maximum of 2 m/s as recommended by “Urban Stormwater Management Manual for Malaysia” (DID, 2000) which was replaced later by “Urban Stormwater Management Manual for Malaysia – 2nd Edition” (DID, 2012). Earlier design manual, namely “Planning and Design Procedures No.1: Urban Drainage Design Standards and Procedures for Peninsular Malaysia” (DID, 1975) recommended a minimum velocity of 0.9 m/s and restricted to a maximum of 3 m/s. The minimum critical velocity value appears to have developed from experience without theoretical justification or underlying research (Butler et al., 1996b). The weakness of minimum critical velocity criterion is that it take no account of the quantity or type of sediment to be transported or of other factors such as sewer size (Butler et al., 1996b; Butler et al., 2003). Table 2.5 gives a summary of available design criteria based on minimum critical velocity as adopted by different countries.

Minimum critical shear stress value τ_c which is considered to be more closely related to the forces causing sediment movement is sometimes used instead of minimum critical velocity criterion. Minimum critical shear stress criteria are used in some European countries and are also implicit in certain traditional UK criteria (Butler et al., 1996b). Same with the case for minimum critical velocity, the use of single minimum critical shear stress value is unrelated to the type and quantity of sediment entering the sewer. Table 2.6 gives a summary of minimum critical shear stress criteria used in various countries.

Table 2.5: Minimum critical velocity criteria (modified from Vongvisessomjai et al., 2010)

Source	Country	Sewer type	Minimum velocity (m/s)	Pipe flow condition
ASCE (1970)	USA	Sanitary	0.6	Full/half full
		Storm	0.9	Full/half full
British Standard BS8005 (1987)	UK	Storm	0.75	Full
		Combined	1.0	Full
Minister of Interior (1977)	France	Sanitary	0.3	Mean daily
		Combined	0.6	1/10 full flow
		Separate	0.3	1/100 full flow
European Standard EN 752-4 (1997)	Europe	All sewers	0.7 once/day for pipe D < 300 mm 0.7 or more if necessary for pipe D > 300 mm	N/A
Abwassertechnische Verreinigung ATV, Standard A 110 (1998) replaced by ATV-DVWK-Regelwerk (2001)	Germany	Sanitary Storm Combined	Depends on pipe diameter ranging from 0.48 (D = 150 mm) to 2.03 (D = 3000 mm)	0.3 to full for 0.1 to 0.3, velocity plus 10%
Almedeij (2012)	Kuwait	Storm	0.75	Rectangular open channel
DID (1975)	Malaysia	Storm	0.9	Lined channel
DID (2000) replaced by DID (2012)	Malaysia	Storm	0.6	Open lined drain

Table 2.6: Minimum critical shear stress criteria (modified from Vongvisessomjai et al., 2010)

Source	Country	Sewer type	Minimum shear stress (N/m^2)	Pipe flow condition
Lysne (1969)	USA		2.0 – 4.0	
ASCE (1970)	USA		1.3 – 12.6	
Yao (1974)	USA	Storm	3.0 – 4.0	
		Sanitary	1.0 – 2.0	
Maguire rule (CIRIA 1986)	UK		6.2	Full/half full
Lindholm (1984)	Norway	Combined	3.0 – 4.0	
		Separate	2.0	
Scandiaconsult (1974)	Sweden	All	1.0 – 1.5	1.5 if sand is present
Macke (1982)	Germany	Sanitary Storm Combined	Depends on transport capacity and concentration	0.1 to full typical combined sewers under long term conditions
Brombach et al. (1992)	Germany	Combined	1.6 to transport 90% of all sediments	

Rather than just using a single value, the non-deposition design concept was further modified to use more parameters in the 1990s which resulted in the without deposition design criteria and with limited deposition design criteria (Vongvisessomjai et al., 2010).

2.3.1.1 Without Deposition Design Criteria

This is a conservative design criterion where the sewer is designed with no sediment deposit. In this design criterion, the mode of transport must be identified; either as suspended load or bed load in order to use an existing self-cleansing equation (Vongvisessomjai et al., 2010). Suspended load travels at almost the same velocity with surrounding water and the shape of the vertical profile depends on the parameter u_* / W_s where W_s is the fall velocity of the sediment [m/s] and u_* is the shear velocity of the flow [m/s] defined as:

$$u_* = \sqrt{\left(\frac{\tau_c}{\rho}\right)} \tag{2.7}$$

where τ_c is the critical shear stress [N/m^2] and ρ is the density of liquid [kg/m^3]. For flow conditions and sediment particles that give values of $u_* / W_s < 0.75$, the movement will be mainly as bed load; while for $u_* / W_s > 0.75$, the sediment moves in suspension (May et al., 1996). The point of transition is termed limit of deposition.

For bed load transport, May et al. (1996) combined seven formulas from different experimental laboratory test and obtained:

$$C_v = 3.03 \times 10^{-2} \left(\frac{D^2}{A}\right)\left(\frac{d_{50}}{D}\right)\left[1 - \frac{V_c}{V_L}\right]\left[\frac{V_L^2}{gD(s-1)}\right]^{1.5} \tag{2.8}$$

$$V_c = 0.125\left[g(s-1)d_{50}\right]^{0.5}\left[\frac{y}{d_{50}}\right]^{0.47} \quad (2.9)$$

where C_v is volumetric sediment concentration [ppm]; D is pipe diameter [m]; d_{50} is median particle size larger than 50% by mass [m]; V_L is self-cleansing velocity [m/s]; y is water depth [m]; and V_c is critical velocity [m/s]. May et al. (1996) claimed Equations (2.8) and (2.9) are best fit for 332 individual laboratory tests. The laboratory tests conditions covered by the data included: pipe diameters from 77 mm to 450 mm; sediment size from 160 µm to 8300 µm; flow velocities from 0.24 m/s to 1.5 m/s; proportional flow depth $\left(\frac{y}{D}\right)$ from 0.16 m to 1 m; and sediment concentrations from 2.3 ppm to 2110 ppm. During bed load transport, sediment particles move much slower relative to the flow than those carried in suspension. A study on particle velocity in sediment transport over clean fixed bed has shown that the sediment particle velocity, even for the fastest moving particle is as low as about half of the mean flow velocity (Ota and Perrusquia, 2013).

For suspended load, Equation (2.10) was plotted by Macke (1982) with data from other studies (Durand, 1953; Einstein and Chein, 1955; Robinson and Graf, 1972).

$$C_v = \frac{\lambda_0{}^3 V_L^5}{30.4(s-4)W_s^{1.5}A} \quad (2.10)$$

where C_v is volumetric sediment concentration [ppm]; λ_0 is the Darcy-Weisbach friction factor; W_s is the fall velocity [m/s]; A is flow area cross-section [m^2]; and V_L is self-cleansing velocity [m/s]. Equation (2.10) is based on experiments for sediment diameter from 0.16 mm to 0.37 mm; pipe diameters of 192 mm, 290 mm