Self-Cleansing Design of Rectangular Open Storm Sewer

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ABSTRACT
The aim of the present study is to develop incipient motion equation and design chart based on critical velocity approach for the self-cleansing design of rectangular open storm sewer. Data from experimental work on incipient motion from rectangular flumes with two different widths, namely 0.3 m and 0.6 m were subjected to multiple linear regression analysis. Selected regression models for critical velocity were further subjected to performance test by using the data from three different authors in the literature. The best regression model was proposed as the critical velocity equation and was used to develop a self-cleansing design chart. The design chart could be used to determine the minimum slope required for the purpose of self-cleansing design for the respective standard open storm sewer size available from the manufacturer of open concrete rectangular sewer.

KEYWORDS
Critical velocity, incipient motion, open storm sewer, self-cleansing design

INTRODUCTION
Open sewer system has been frequently used in developing country like Malaysia to convey storm water runoff (Bong *et al.*, 2013). Though open sewer system could be quite effective in rapid surface runoff removal; sediment tends to build up after a period of time. For the purpose of self-cleansing design to reduce sedimentation, a minimum average flow velocity of not less than 0.6 m/s has been recommended for lined open drain by “Urban Stormwater Management Manual for Malaysia” (DID, 2000) which was replaced later by “Urban Stormwater Management Manual for Malaysia – 2nd Edition” (DID, 2012). However, the adopted minimum velocity value appear to be developed from experience without underlying research or theoretical justification and no account is taken of the sediment characteristics and hydraulic aspects of the channel (Butler *et al.*, 1996). A more viable approach is to incorporate some aspects of sediment and channel characteristics into self-cleansing design through incipient motion equation (Novak and Nalluri, 1984; El-Zaemey, 1991).

The self-cleansing design criteria for closed conduit sewer are widely available in the literature. Design charts relating the flow discharge with the sewer gradient and pipe diameter (Nalluri and Ab. Ghani, 1996; Butler *et al.*, 2003; Bizier, 2007) have been developed for closed conduit sewers for the purpose of self-cleansing design. Nevertheless, the literature is still lacking on self-cleansing design chart for open sewer system.

This paper highlights the development of incipient motion equation and design chart based on critical velocity approach for the self-cleansing design of rectangular open storm sewer. The experimental work on incipient motion for the present study was conducted in a rectangular flume with the dimensions 6.3 m (L) x 0.6 m (W) x 0.4 m (D). Using multiple linear regression, regression models for critical velocity was developed using the data from the incipient motion experiment and also the data from Salem (1998). The selected regression models were further subjected to performance test using selected data from three different authors in the literatures. Using the best regression model for critical velocity, a design chart was developed. The chart could be used to determine the minimum slope required for the purpose of self-cleansing design for the respective standard drain size available from the manufacturer of open concrete rectangular drain.

CHARACTERISTIC PARAMETERS FOR INCIPIENT MOTION

Based on available studies, the relevant parameters that are used for the analysis of incipient motion based on critical velocity approach are critical velocity V_c, sediment density ρ_s, fluid density ρ, sediment median diameter d_{50}, acceleration due to gravity g, fluid kinematic viscosity ν, bed friction factor λ_0, channel bed width B and flow depth y_0 or hydraulic radius R. Other parameters that could be included are the bed slope S_0 and sediment deposition thickness t_s though the effect on the incipient motion are not well established in the literature (Bong *et al.*, 2013).

The parameters can be grouped into dimensionless group which consists of four categories namely mobility parameter, sediment parameter, conveyance parameter and flow resistance parameter (see Table 1). Some of the parameters may be highly correlated with each other, thus choosing more than one parameter from the same class may not yield any significant changes to the prediction power of the model (Sinnakaudan *et al.*, 2006). This was taken into consideration when choosing variables for multiple linear regression analysis.

Table 1. Characteristic parameters for incipient motion (Novak and Nalluri, 1984; El-Zaemey, 1991; Salem, 1998; Shvidchenko and Pender, 2000; Shvidchenko *et al.*, 2001; Lamb *et al.*, 2008).

Parameter class	Dimensionless group
Mobility	$F_d = \frac{V_c}{\sqrt{gd_{50}(S_s - 1)}}$
Sediment	$D_{gr} = d_{50}\left(\frac{g(S_s - 1)}{\nu^2}\right)^{1/3}, \mathrm{Re}_* = \frac{u_* d_{50}}{\nu}, \frac{\rho_s}{\rho}$
Conveyance	$\frac{y_0}{B}, S_0, \frac{t_s}{y_0}$
Flow resistance	$\frac{d_{50}}{R}, \frac{y_0}{d_{50}}, \lambda_0 = \frac{8gRS_0}{V_c^2}, \frac{t_s}{d_{50}}$

METHODS

The present experimental work involved a rectangular open flume as shown in Figure 1. The velocity and discharge values during the experiment were obtained from an electronic current meter. The non-cohesive uniform sediment used had d_{50} sizes of 0.81 mm, 1.53 mm and 4.78 mm with specific gravity of 2.54, 2.55 and 2.57 respectively. The experiment was conducted at four different slopes (0.005, 0.00286, 0.002 and 0.001) and four different sediment thicknesses (one layer, 5 mm, 10 mm and 24 mm). The definition of incipient motion used in the present experiment was of general movement (Kramer, 1935). The total number of experimental runs conducted in the present study was 48. More information on the experimental procedure for the present study could be referred to Bong *et al.* (2013).

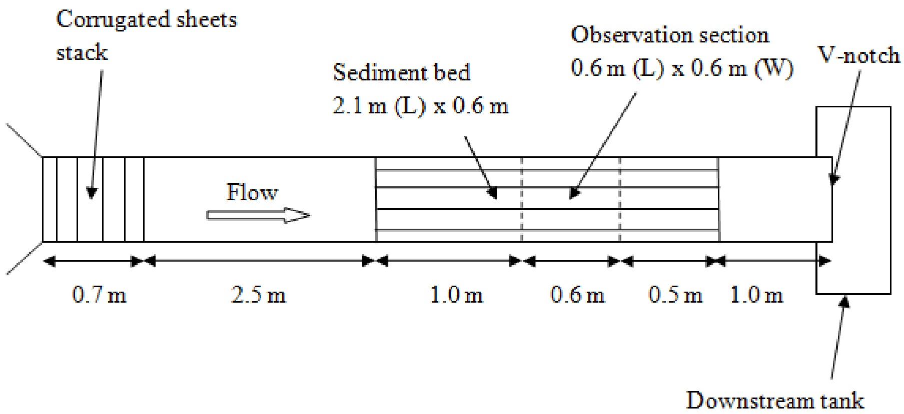

Figure 1. Schematic diagram of the flume.

Another set of experimental data was obtained from Salem (1998) with the number of runs was 119. The range of experimental parameters for both the present study and the study by Salem (1998) were as shown in Table 2. The two sets of data were used to develop incipient motion equation for critical velocity through multiple linear regression. Fitting of all possible regression equation method for selected characteristic parameters was preferable for the purpose of the present study since the possible test cases formed represent only one dimensionless group for each parameter class. Four criteria were used to select the best regression model which were based on: (a) coefficient of determination R_p^2; (b) mean square error MSE; (c) Mallow's C_p statistics and (d) adjusted R_{adj}^2 (Sinnakaudan et al., 2006). The critical velocity equation was then subjected to performance test using data from Yalin and Karahan (1979), Kuhnle (1993) and Shvidchenko (2000) (see Table 3). For the performance test, the discrepancy ratio was calculated using Equation (1) with the acceptable range of 0.5 – 2.0 which is normally used for study on sediment transport (Yang, 1996).

$$\text{Discrepancy ratio} = \frac{V_c \text{ predicted (m/s)}}{V_c \text{ observed (m/s)}} \tag{1}$$

Table 2. Range of experimental parameters for present study and Salem (1998).

Parameter	Present study	Salem (1998)
Flume width W (m)	0.6	0.3
Critical velocity V_c (m/s)	0.216 – 0.442	0.188 – 0.619
Normal flow depth y_0 (m)	0.007 – 0.132	0.013 – 0.154
Reynolds number Re	7878.90 – 163512.50	11571.45 – 222440.60
Flume slope S_0	0.001 – 0.005	0.0005882 – 0.002
Sediment size d_{50} (mm)	0.81 – 4.78	0.55 – 4.78
Sediment specific gravity S_s	2.540 – 2.570	2.301 -2.569
Sediment thickness t_s (mm)	0.81 – 24.00	0.55 – 24.00

Table 3. Range of experimental data from Yalin and Karahan (1979), Kuhnle (1993) and Shvidchenko (2000).

Parameter	Yalin and Karahan (1979)	Kuhnle (1993)	Shvidchenko (2000)
Flume width, W (m)	0.760	0.356	0.300
Critical velocity, V_c (m/s)	0.208 – 0.288	0.279 – 3.154	0.065 – 0.865
Normal flow depth, y_0 (m)	0.046 – 0.065	0.095 – 0.107	0.015 – 0.136
Flume slope, S_0	0.00300 – 0.01000	0.00038 – 0.01337	0.00190 – 0.01570
Sediment size, d_{50} (mm)	0.100 – 1.000	0.476 – 5.579	1.500 – 2.400
Sediment specific gravity, S_s	2.65	2.65	2.60 – 2.65

RESULTS AND DISCUSSION

Pearson correlation analysis was done between the particle Froude number F_d with the other characteristic parameters. Table 4 summarises the Pearson correlation coefficient and significance *p*-value for each of the characteristic parameter. Only characteristic parameters with weak correlation (between +0.3 and +0.7 or -0.3 and -0.7) and above were selected from Table 4 for multiple linear regression analysis. The four best models were as shown in Table 5.

Table 4. Correlation analysis for F_d with the other characteristic parameters.

Characteristic parameter	F_d
D_{gr}	-0.598 (*p*-value = 0.000)
Re_*	-0.647 (*p*-value = 0.000)
$\frac{\rho_s}{\rho}$	-0.004 (*p*-value = 0.962)
$\frac{y_0}{B}$	-0.076 (*p*-value = 0.330)
S_0	-0.398 (*p*-value = 0.000)
$\frac{t_s}{y_0}$	0.288 (*p*-value = 0.000)
$\frac{d_{50}}{R}$	-0.510 (*p*-value = 0.000)
$\frac{y}{d_{50}}$	0.474 (*p*-value = 0.000)
λ_0	-0.588 (*p*-value = 0.000)
$\frac{t_s}{d_{50}}$	0.496 (*p*-value = 0.000)

Table 5. Selected regression models for critical velocity approach.

Equation	R^2	R^2_{adj}	*MSE*	C_p	Equation No.
$\frac{V_c}{\sqrt{gd_{50}(S_s-1)}} = 2.14(D_{gr})^{-0.178}(\lambda_0)^{-0.200}$	0.736	0.733	0.0023	5.0087	(2)
$\frac{V_c}{\sqrt{gd_{50}(S_s-1)}} = 3.00(D_{gr})^{-0.182}(S_0)^{0.073}(\lambda_0)^{-0.248}$	0.753	0.748	0.0022	5.8571	(3)
$\frac{V_c}{\sqrt{gd_{50}(S_s-1)}} = 1.94(\mathrm{Re}_*)^{-0.121}(\lambda_0)^{-0.163}$	0.664	0.660	0.0029	5.2055	(4)
$\frac{V_c}{\sqrt{gd_{50}(S_s-1)}} = 2.80(\mathrm{Re}_*)^{-0.125}(S_0)^{0.079}(\lambda_0)^{-0.213}$	0.684	0.678	0.0028	6.2347	(5)

The selected regression models in Table 5 were subjected to performance test using data from Yalin and Karahan (1979), Kuhnle (1993) and Shvidchenko (2000). For the data from Yalin and Karahan (1979), five data from the experiment in turbulent flow were selected out of a total of 22 (16 laminar flows and six turbulent flows). The rest of the data were not selected due to the flow medium used in the laminar flow condition was of glycerine and water mixture and not purely water whereas one data from the turbulent flow was using glass beads as sediment. As for the data from Kuhnle (1993), only 12 data of uniform sediment with unimodal characteristics were chosen out of a total of 30 data. For data from Shvidchenko (2000), 83 out of 312 data were chosen. The data were chosen only for the experiment with transport intensities within the two critical values of $I = 10^{-4}$ s^{-1} and $I = 10^{-2}$ s^{-1} as defined by Shvidchenko (2000) and also for gravel size not more than 5.65 mm. Table 6 shows the result of performance test for the selected regression models.

Table 6. Performance test for selected regression models.

Data source (no. of data)	Data within acceptable discrepancy ratio (0.5 – 2.0)			
	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)
Yalin and Karahan (5)	4 80%	4 80%	4 80%	4 80%
Kuhnle (12)	7 58.3%	6 50.0%	7 58.3%	7 58.3%
Shvidchenko (83)	82 98.8%	82 98.8%	82 98.8%	82 98.8%
Total (100)	93 93%	92 92%	93 93%	93 93%

From Table 5, Equation (3) was the best among the selected regression models with R^2 and R^2_{adj} values closest to unity and having the smallest MSE value together with reasonable C_p value which was close to the number of variables in the model. In Table 6, all the selected regression models performed similarly well. Thus, Equation (3) was chosen to develop the design chart for self-cleansing and could be rewritten as:

$$V_c = \left(\left(\frac{3.00 (D_{gr})^{-0.182} (S_0)^{0.073} \sqrt{g d_{50} (S_s - 1)}}{(8gRS)^{0.248}} \right) \right)^{1.984} \tag{6}$$

Assuming that Equation (6) could be extended to wider channel instead of just the flume widths used in the experimental works for the development of the equation, the assumption for the parameters made for the development of a self-cleansing design chart were as summarised in Table 7. Using Equation (6) with the assumptions in Table 7; the critical velocity V_c could be calculated and hence the design minimum flow rate $(Q_{\min} = AV_c)$. Figure 2 shows the design chart for self-cleansing design relating the open storm sewer minimum slope S_0 with the design minimum flow rate $Q_{\min}$ for the respective open storm sewer size for the condition of sediment size d_{50} = 1.0 mm and $y_0 = B$. Also shown in Figure 2 was the minimum velocity criteria V_c = 0.6 m/s for current practice as plotted in dashed line. It could also be observed from Figure 2 that the current design criteria based on minimum velocity of 0.6 m/s tended to over design in terms of required minimum design slope for smaller open storm sewer sizes (600 mm x 600 mm; 750 mm x 750 mm and 900 mm x 900 mm) whereas tended to under design the required minimum design slope for larger open storm sewer (1500 mm x 1500 mm and 1800 mm x 1800 mm). It should be noted that a somewhat different chart would emerge for sediment of different size and different flow depth to open storm sewer depth ratio; however Equation (6) could still be used for the calculation to develop the new chart if necessary.

To use the design chart in Figure 2 for self-cleansing design purpose of open storm sewer; first, the open storm sewer size and its slope capacity need to be determined. To determine the size of the open storm sewer, the peak flow rate needs to be calculated for the drainage area. The slope could be determined from the topography or energy head required to carry the peak flow rate. After the open storm sewer size and slope are determined, the slope needs to be checked with Figure 2 for the related open storm sewer size. This is to determine whether a steeper slope is required for self-cleansing. If it is required, then the open storm sewer minimum slope for self-cleansing S_{min} becomes the design slope for the corresponding discharge rate.

Table 5. Assumptions for development of self-cleansing design chart.

Parameter	Assumption
Open storm sewer shape	Square $(y_0 = B)$
Open storm sewer size (mm)	600 x 600; 750 x 750; 900 x 900; 1200 x 1200; 1500 x 1500; 1800 x 1800
Flow condition	Full flow
Sediment specific gravity S_s	2.65
Kinematic viscosity of water ν (m^2/s)	1.004×10^{-6}
Open storm sewer slope S_0	0.0005882 – 0.005
Sediment size d_{50} (mm)	1.0

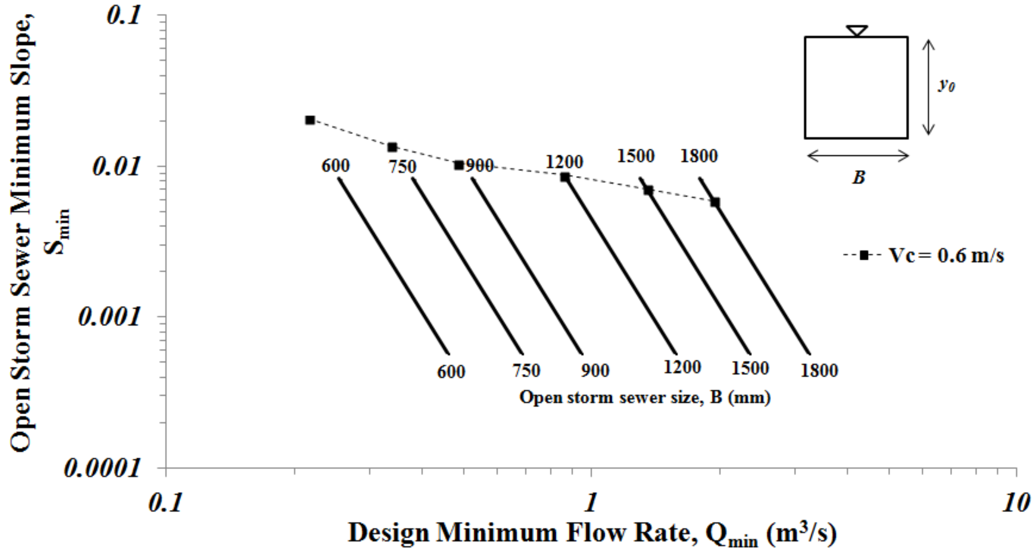

Figure 2. Self-cleansing design relationship between open storm sewer minimum slope and design minimum flow rate with the respective open storm sewer size (sediment size d_{50} = 1.0 mm and full flow).

CONCLUSION

The present study highlights the development of incipient motion equation and design chart based on critical velocity approach for the self-cleansing design of rectangular open storm sewer. Incipient motion experiment was conducted in a rectangular flume. Using multiple linear regression, regression models for critical velocity was developed using the data from the incipient motion experiment and also the data from Salem (1998). Selected regression models were subjected to performance test using data from three other authors in the literature. The best regression model was chosen to develop a self-cleansing design chart. The design chart simplifies the design procedure in determining the open storm sewer minimum slope and the design minimum flow rate for the respective open storm sewer size.

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REFERENCES

Bizier, P. (ed.) (2007). *Gravity sanitary sewer design and construction,* Reston, Virginia: American Society of Civil Engineers (ASCE).

Bong, C. H. J., Lau, T. L. and Ghani, A. A. (2013). Verification of equations for incipient motion studies for a rigid rectangular channel. *Water Science and Technology*, 67(2), 395-403.

Butler, D., May, R. and Ackers, J. (2003). Self-cleansing sewer design based on sediment transport principles. *Journal of Hydraulic Engineering,* 129(4), 276-282.

Butler, D., May, R. W. P. and Ackers, J. C. (1996). Sediment transport in sewers part 2: design. *Proc. Instn Civ. Engrs Wat., Marit. & Energy*, 118(2), 113-120.

DID (2000). *Urban stormwater management manual for Malaysia*, Kuala Lumpur, Malaysia: Department of Irrigation and Drainage, Malaysia.

DID (2012). *Urban stormwater management manual for Malaysia - 2nd edition*, Kuala Lumpur, Malaysia: Department of Irrigation and Drainage, Malaysia.

El-Zaemey, A. K. S. (1991). *Sediment transport over deposited bed sewers.* Ph.D thesis, University of Newcastle upon Tyne.

Kramer, H. (1935). Sand mixtures and sand movement in fluvial models. *Transaction, ASCE,* 100**,** 798-878.

Kuhnle, R. A. (1993). Incipient motion of sand-gravel sediment mixtures. *Journal of Hydraulic Engineering*, 119(12), 1400-1415.

Lamb, M. P., Dietrich, W. E. and Venditti, J. G. (2008). Is the critical Shields stress for incipient motion sediment motion dependent on channel-bed slope? *Journal of Geophysical Research,* 113(F2).

Nalluri, C. and Ab. Ghani, A. (1996). Design options for self-cleansing storm sewers. *Water Science and Technology*, 33(9), 215-220.

Novak, P. and Nalluri, C. (1984). Incipient motion of sediment particles over fixed beds. *Journal of Hydraulic Research*, 22(3), 181 - 197.

Salem, A. M. (1998). *Incipient motion over loose deposited beds in a rigid rectangular channel.* MSc. thesis, Universiti Sains Malaysia.

Shvidchenko, A. B. (2000). *Incipient motion of streambeds*. Ph.D thesis, University of Glasgow, Glasgow, United Kingdom.

Shvidchenko, A. B. and Pender, G. (2000). Flume study of the effect of relative depth on the incipient motion of coarse uniform sediments. *Water Resources Research*, 36(2), 619-628.

Shvidchenko, A. B., Pender, G. and Hoey, T. B. 2001. Critical shear stress for incipient motion of sand/gravel streambeds. *Water Resources Research*, 37(8), 2273-2283.

Sinnakaudan, S. K., Ab. Ghani, A., Ahmad, M. S. S. and Zakaria, N. A. (2006). Multiple linear regression model for total bed material load prediction. *Journal of Hydraulic Engineering*, 132(5), 521-528.

Yalin, M. S. and Karahan, E. (1979). Inception of sediment transport. *Journal of Hydraulic Division*, 105(11), 1433-1443.

Yang, C. T. (1996). *Sediment transport: theory and practice*, Singapore, McGraw-Hill.