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A GENERAL SELF-CLEANSING MODEL FOR DRAINAGE SYSTEM DESIGN

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Self-cleansing is a design criterion that satisfies a condition to keep a channel bottom clean from sediment deposits. Deposition of sediment significantly affects on the hydraulic capacity of the channel, and therefore additional costs arise for cleaning the channel. Self-cleansing models in literature are mostly developed for circular channels, which make the limited applicability of existing models. In this study, using experimental data of different cross-section channels, a self-cleansing model is suggested for computation of non-deposition particle Froude number. Considering open channel flow resistance, and using simple channel geometry parameters, a channel cross-section shape factor is incorporated into the model to make it applicable for any arbitrary channel cross-section shape. The robustness of the model is evaluated on different cross-section experimental data to show the applicability of the model on a variety of channel cross-section.

KEY WORDS: cross-section; drainage system; sediment transport; self-cleansing; sewer

1. INTRODUCTION

Sewer and urban drainage systems must be designed in a way to minimize continues deposition of sediment. Uncontrolled deposition of sediment significantly affects the hydraulic capacity of the system by reducing channel cross-section area. Also, additional costs arise for cleaning the deposited sediment. In order to prevent aforementioned problems, drainage systems are designed based on self-cleansing concept.

Self-cleansing is a hydraulic design criteria that satisfies a condition in which flow has a capability to remove sediment from channel bottom or sediment particles which are transported through the flow never be deposited. The former concept includes incipient motion and scouring criteria (Safari, 2016) while the latter covers non-deposition criteria of with and without deposited bed; and incipient deposition criteria (Ab Ghani, 1993; May, 1993; May et al., 1996; Ota and Perrusquia, 2013; Safari et al., 2015, 2016). Non-deposition without deposited bed criterion is the most conservative method for channel design which keeps the channel bottom clean from sediment deposits.

Conventionally, in the non-deposition without deposited bed self-cleansing design criterion, a single value of flow mean velocity or average bed shear stress was used (CIRIA, 1986; Vongvisessomjai et al., 2010; Safari, 2016). Although minimum shear stress value (1-12.6 N/m^2) is used in some cases, the minimum velocity (0.3-1 m/s) is mostly adopted in many countries. There are several deficiencies in the conventional method in which many important factors like quantity, type of sediment and sewer size are missing. To this extend, considering more hydraulic parameters, non-deposition self-cleansing models were developed to modify the conventional self-cleansing criteria. The self-cleansing models mostly developed for the bed load sediment transport as it is close to the permanent deposition condition. However, the models were suggested mostly for circular and in some cases for rectangular channels. Therefore, applicability of existing models in the literature for any arbitrary cross-section channel is questionable.

This study is aimed to recommend a non-deposition bed load self-cleansing model applicable for any channel cross-section by incorporating a cross-section shape factor in the model. The model is compared with the corresponding models in the literature to show its robustness.

2. NON-DEPOSITION WITHOUT DEPOSITED BED SELF-CLEANSING CRITERION

Instead of using a single value of velocity or shear stress for drainage system design, in the recent decades self-cleansing models have been developed for computing minimum velocity and shear stress in non-deposition condition considering flow, fluid, sediment and channel characteristics. The models were suggested for suspended load or bed load. There are a few studies for investigation of non-deposition condition of suspended load (Nalluri and Spaliviero, 1998); however, bed load were mostly considered in many studies due to large particles are transported as bed load through the flow. May (1993) and May et al. (1996) studied non-deposition condition in circular pipe channels while Mayerle et al. (1991) studied rectangular and circular channels. Loveless (1992) studied the non-deposition and incipient deposition of bed load in different cross-section channels and evaluated the applicability of models proposed by Ackers and White (1973) and May (1982). Ab Ghani (1993) investigated the effect of pipe size in the non-deposition condition of bed load and found that the larger pipe sizes required higher self-cleansing velocity. Ota and Perrusquia (2013) conducted experiments in pipes and additional parameters such as particle velocity, sediment shape factor, sediment angle of repose and channel roughness were considered in the analysis. Vongvisessomjai et al. (2010) studied the non-deposition in suspended load and bed load in circular channels and recommended self-cleansing models for the bed and suspended loads. Safari et al. (2017) performed experiments for determination of non-deposition condition in a trapezoidal cross-section channel and extended the formerly developed non-deposition models by incorporating channel cross-section shape factor into the model for wider applicability. The model was developed using their own data together with Loveless (1992) non-deposition data.

Examples from the literature models of Mayerle et al. (1991), Ab Ghani (1993), Vongvisessomjai et al. (2010) and Safari et al. (2017) are listed in Table 1.

Table 1

Selected bed load non-deposition without deposited bed models

Equation	Reference	Eq. No.
$\frac{V_n}{\sqrt{gd(s-1)}} = 14.43 C_v^{0.18} D_{gr}^{-0.14} \left(\frac{d}{R}\right)^{-0.56} \lambda^{0.18}$	Mayerle et al. (1991)	(1)
$\frac{V_n}{\sqrt{gd(s-1)}} = 3.08 C_v^{0.21} D_{gr}^{-0.09} \left(\frac{R}{d}\right)^{0.53} \lambda^{-0.21}$	Ab Ghani (1993)	(2)
$\frac{V_n}{\sqrt{gd(s-1)}} = 4.31 C_v^{0.226} \left(\frac{d}{R}\right)^{-0.616}$	Vongvisessomjai et al. (2010)	(3)
$\frac{V_n}{\sqrt{gd(s-1)}} = 7.34 C_v^{0.13} D_{gr}^{-0.12} \left(\frac{d}{R}\right)^{-0.44} \beta^{-0.91}$	Safari et al. (2017)	(4)

(V: non-deposition flow velocity; g: gravitational acceleration; d: sediment median size; s: sediment relative specific mass: C_v: volumetric sediment concentration; R: hydraulic radius; λ: Darcy-Weisbach friction factor; $D_{gr} = \left((s-1)gd^3/\nu^2\right)^{1/3}$: grain size parameter; ν: kinematic viscosity of fluid; β: channel cross-section shape factor)

The left hand side in the models shown in Table 1 is particle Froude number (Fr_p) and d/R is relative particle size. Mayerle et al. (1991), Ab Ghani (1993) and Vongvisessomjai et al. (2010) models are developed for circular channels, while in Safari et al. (2017) model channel cross-section shape factor is incorporated in the model which is valid for any cross-section shape.

3. CROSS-SECTION SHAPE FACTOR

It is reported by Yen (2002) that the shape of the channel cross-section affects the flow resistance. Experimental studies of Knight et al. (1984) indicated that non-uniform distribution of shear stress over the wetted perimeter in open channels depends on the channel cross-section shape. Resistance to flow in open channels is greater than the equivalent full pipe flow at the same Reynolds number (Safari et al., 2017). Therefore, treatment of an open channel as an equivalent pipe cannot represent the effect of cross-section shape (Nalluri and Adepoju, 1985). Rouse (1965) reported that change in the cross-section shape affects the resistance to flow in two ways in which firstly, the value of wetted perimeter per unit cross-section area changes; and secondly, it causes the change in the shear stress distribution over the wetted perimeter.

Jayaraman (1970), Kazemipour and Apelt (1979, 1982), Nalluri and Adepoju (1985), Paul and Sakhuja (1990) and Nalluri and Ab Ghani (1993) used channel geometry parameters for describing the effect of channel cross-section shape. Among those, the Kazemipour and Apelt (1979) method has theoretical background which can best describe the effect of channel cross-section shape. Kazemipour and Apelt (1979) demonstrated that P/B and B/D_h reflect the effect of the non-uniform distribution of the shear stress on the channel boundary. Here P is the wetted perimeter, B the water surface width and D_h the hydraulic depth of flow (A/B, A is cross-section area). Using aforementioned geometric parameters they reduced and adjusted the open channel friction factor to an equivalent pipe at the same Reynolds number. The detail computation procedure can be found in Kazemipour and Apelt (1979) and Safari et al. (2017). Applying the same methodology, Safari et al. (2017) recommended

$$\beta = \frac{\sqrt{P/B}}{1.31\left(B/D_h\right)^{-0.49}} \tag{5}$$

as a channel cross-section shape factor. It is seen that the exponent of B/D_h is -0.49, therefore, by assuming the exponent as -0.50 the β can be reduced to

$$\beta = 0.76\sqrt{\frac{B}{R}} \tag{6}$$

It can be said that Eq. (6) is simpler than Eq. (5) and parameter of B/R can best describe the channel cross-section shape effect.

4. EXPRIMENTAL DATA

Loveless (1992) and Safari et al. (2017) non-deposition bed load data are used in this study. Loveless (1992) studied the bed load sediment transport in the incipient deposition and non-deposition conditions in rectangular, circular and U-shape cross-section channels using sediment size ranging from 0.45-6 mm. The circular channel had a diameter of 8.8 cm while the rectangular one had a width of 10 cm and height of 5.9 cm. Both conduits were constructed in length of 7.2 m with a cross-sectional areas of approximately 60 cm^2. The U-shape channel is 22 cm wide, 40 cm deep and 7.0 m long. Safari et al. (2017) conducted experiments in a trapezoidal cross-section channel 12 m long with a 30 cm bottom width. The inclined length of each side wall was 30 cm with an outer angle of 600 using sands sizes ranging from 0.15-0.83 mm. As reported by CIRIA (1986) the sediments in real sewers systems are with the range of 0.1-9 mm. The range of sediment used in the experiments were 0.15-7.2 mm which are quite suitable for extension of results for real drainage systems.

5. RESULTS AND DISCUSSION

5.1. GENERAL SELF-CLEANSING MODEL

Flow, fluid, sediment and channel characteristics are of importance for modeling sediment transport in drainage systems. To this end, flow velocity (V), hydraulic radius (R), gravitational acceleration (g), fluid kinematic viscosity (v) and density (ρ), sediment density (ρ_s), sediment median size (d), volumetric sediment concentration (C_v), and channel cross-section shape factor (β) are considered for model development. As it is shown in Eq. (2), β can be replaced by a simple expression of B/R as channel cross-section shape factor. Reviewing the models available in the literature the aforementioned variables can be written as

$$\frac{V}{\sqrt{gd(s-1)}} = f\left(C_v, \frac{d}{R}, \frac{B}{R}\right) \tag{7}$$

Using rectangular, circular, U-shape and trapezoidal cross-section channels experimental data taken from Loveless (1992) and Safari et al. (2017)

$$\frac{V}{\sqrt{gd(s-1)}} = 3.59C_v^{0.11}\left(\frac{d}{R}\right)^{-0.51}\left(\frac{B}{R}\right)^{-0.37} \tag{8}$$

is recommended as a general bed load self-cleaning model.

5.2. EVALUATION OF THE MODELS

The developed model in this study is compared with corresponding models in the literature namely; Mayerle et al. (1991), Ab Ghani (1993), Vongvisessomjai et al. (2010) and Safari et al. (2017). Two statistical performance criteria; the mean absolute percentage error (*MAPE*) and the mean performance index (*MPI*) are used for models evaluation. The *MAPE* gives the model accuracy as the percentage, and it is given by

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\left(Fr_p^c\right)_i - \left(Fr_p^m\right)_i}{\left(Fr_p^m\right)_i}\right| \times 100 \tag{9}$$

in which Fr_p^c and Fr_p^m, respectively, are the calculated and measured particle Froude numbers in the non-deposition condition; and n the number of data. The mean performance index (*MPI*) is used to check the model robustness and calculated by

$$MPI = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(Fr_p^c\right)_i}{\left(Fr_p^m\right)_i} \times 100 \tag{10}$$

with a perfect agreement at 100%. *MPI* lower than 100% shows an underestimation while a higher value corresponds an overestimation.

Table 2 shows the *MAPE* and *MPI* values of all models for each cross-section data. It is seen that models of Mayerle et al. (1991), Ab Ghani (1993) and Vongvisessomjai et al. (2010), Eqs. (1-3) have no high performances for all cross-sections. They have poor performances on the trapezoidal and rectangular cross-sections data. Ab Ghani (1993) and Vongvisessomjai et al. (2010) models, Eqs. (2-3) give good results for the circular and U-shape cross-sections but they are less accurate for the rectangular and trapezoidal cross-sections. This can be justified by the fact that the Ab Ghani (1993) and Vongvisessomjai et al. (2010) models were developed based on circular cross-section data. It can be said that a model developed for a certain channel cross-section does not necessarily give accurate results for other cross-sections. Results shown in Table 2 in terms of *MAPE* indicate that the developed model in this study (Eq. 8) and Safari et al. (2017) model Eq. (4) generate good performances in all cross-sections for predicting the particle Froude number in the non-deposition condition. Although Eq. (8) and Safari et al. (2017) model, Eq. (4) have nearly performances, Eq. (8) provides slightly better performance than Safari et al. (2017) model. Considering *MAPE* values shown in Table 2, Eq. (8) outperforms all other models on circular, U-shape and trapezoidal channels, while for rectangular one, the Safari et al. (2017) model gives slightly better performance.

Table 2

Comparison of Equation (4) with models in the literature on each cross-section data

Cross-section	Eq. (1)		Eq. (2)		Eq. (3)		Eq. (4)		Eq. (8)	
	MAPE (%)	*MPI* (%)	*MAPE* (%)	*MPI* (%)	*MAPE* (%)	*MPI* (%)	*MAPE* (%)	*MPI* (%)	*MAPE* (%)	*MPI* (%)
Rectangular	91.79	191.79	17.90	116.67	29.21	128.01	16.51	109.69	17.02	108.69
Circular	72.88	172.88	14.56	108.25	24.06	119.44	10.59	106.24	10.06	103.27
U-shape	25.60	125.61	12.02	92.26	12.47	93.01	5.04	95.43	4.77	96.69
Trapezoidal	227.76	327.76	23.19	122.84	48.53	148.52	13.52	91.18	10.50	94.95

It can be found from Table 2 that Eq. (8) and Safari et al. (2017), Eq. (4) model highly perform for calculating the non-deposition particle Froude number based on the *MPI*. The *MPI* for all cross-section channels are close to 100% indicating that the developed model fits very well to the measurement although a slight underestimation for the trapezoidal and U-shape cross-section channels, and a slight overestimation for the circular and rectangular cross-section channels should be noticed. Based on *MPI* analysis, Eq. (8) is found superior to all models available in the literature, although the Safari et al. (2017), Eq. (4) can compete well with the Eq. (8) developed in this study.

Comparison of models in terms of goodness-of-fit by scatter plots of the measured and calculated particle Froude numbers on four cross-sections data is shown in Figure 1. It is seen that particle Froude numbers calculated by Eq. (8) and Safari et al. (2017) model, Eq. (4) match well the measured particle Froude numbers for the four cross-sections. It has to be emphasized that Eq. (8) results are close to the best-fit line in comparison with Safari et al. (2017) model. Mayerle et al. (1991), the Ab Ghani (1993) and Vongvisessomjai et al. (2010) models, Eqs. (1-3) overestimate particle Froude numbers for the rectangular and trapezoidal cross-section channels. The better performance of Eq. (8) and Safari et al. (2017) model, Eq. (4) can be linked to the incorporating channel cross-section factor into the models. Additional to the slightly better performance of Eq. (8) in comparison with Safari et al. (2017), Eq. (8) is simpler and has no complicated computation procedure. It makes the Eq. (8) an engineering practical tool for channel design.

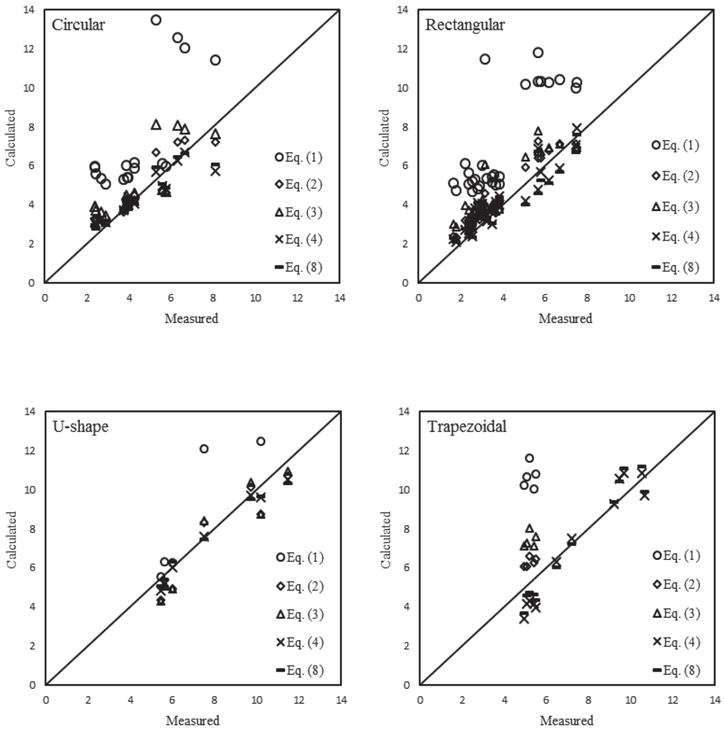

Fig. 1 Comparison of self-cleansing models in terms of measured and calculated particle Froude numbers on each cross-section data

6. CONCLUSION

Considering flow, fluid, sediment and channel characteristics, and using the particle Froude number, the volumetric sediment concentration, the relative particle size and channel cross-section shape factor, a general self-cleansing model is developed in this study. Rectangular, circular, U-shape and trapezoidal cross-section experimental data are used for model development. The cross-section shape factor suggested in this study is simpler than its counterparts available in the literature which makes it a practical tool for the channel design. Comparison of the model developed in this study with the models available in the literature indicates its superior for computing the non-deposition particle Froude number on variety of channel cross-section shapes.

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