A Review on the Self-Cleansing Design Criteria for Sewer System

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Abstract – Sediment deposits in sewer system had been known to have adverse effects on the hydraulic performance of the system and also on the environment. Thus, the need for sewer system to carry sediment has been recognized for many years and self-cleansing criteria have been proposed in the literature for design purposes. Conventionally, a minimum critical velocity or critical shear stress was specified and although this approach had been successful in many cases; it was appreciated that a minimum critical velocity or critical shear stress which is unrelated to the characteristics and concentration of the sediment or the hydraulic behavior of the sewer could not properly represent the ability of the sewer flows to transport sediments. A more viable approach for self-cleansing design is to incorporate some aspect of the sediment and sewer characteristics into the design criteria; hence, various self-cleansing design criteria for sewer have been proposed in the literature. This paper presents a review on the various self-cleansing design criteria for sewer and proposed some further studies that could be conducted to improve the existing self-cleansing design criteria.

Keywords**:** Sediment, Self-cleansing design, Sewer system

I. INTRODUCTION

SEDIMENT deposition in sewer system had caused many adverse effect such as reduction in hydraulic capacity and environmental pollution due to the high pollutant concentrations that might be released during the erosion of these deposition [1-3]. To reduce sediment deposition, sewer system has been designed to have self-cleansing properties. In the design for sewer 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" [4, 5]. A search in the literature for self-cleansing design of sewer will generally categorizes 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 [6]. The design concepts in each group could be classified further into smaller groups as shown in Figure 1.

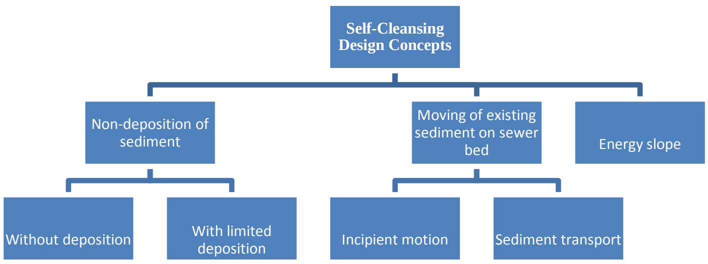

Figure 1 Classification of self-cleansing design concepts from the literature [6, 7]

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II. 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 [4]. 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 [4]. 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 sewer 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" [8] which was replaced later by "Urban Stormwater Management Manual for Malaysia – 2nd Edition" [9]. Earlier design manual, namely "Planning and Design Procedures No.1: Urban Drainage Design Standards and Procedures for Peninsular Malaysia" [10] 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 [4]. The weakness of minimum critical velocity criteria is that it takes no account of the quantity or type of sediment to be transported or of other factors such as sewer size [4, 5]. Table 1 gives a summary of available design criteria based on minimum critical velocity as adopted by different countries.

Table 1 Minimum critical velocity criteria [6, 7]

Source	Country	Sewer type	Minimum velocity (m/s)	Pipe flow condition
ASCE (1970)	USA	Sanitary Storm	0.6 0.9	Full/half full Full/half full
British Standard BS8005 (1987)	UK	Storm Combined	0.75 1.0	Full Full
Minister of Interior (1977)	France	Sanitary Combined Separate	0.3 0.6 0.3	Mean daily 1/10 full flow 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 sewer

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 criteria. Minimum critical shear stress criteria is used in some European countries and is also implicit in certain traditional UK criteria [4]. 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 gives a summary of available design criteria based on minimum critical shear stress criteria used in various countries. 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 [6].

Table 2 Minimum critical shear stress criteria [6]

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	

A. Without Deposition Design Criteria

This is a conservative design criteria where the sewer is designed with no sediment deposit. In this design criteria, the mode of transport must be identified; either as suspended load or bed load in order to use an existing self-cleansing equation [6]. 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:

$$u_* = \sqrt{\left(\frac{\tau_c}{\rho}\right)} \tag{1}$$

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 [11]. The point of transition is termed limit of deposition.

For bed load transport, May et al. [11] combined seven formulas from different experimental laboratory test and obtained:

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

$$V_c = 0.125\left[g(s-1)d_{50}\right]^{0.5}\left[\frac{y}{d_{50}}\right]^{0.47} \tag{3}$$

where C_v is volumetric sediment concentration [ppm]; D is pipe diameter [m]; A is flow area cross-section [m^2]; d_{50} is median particle size larger than 50% by mass [m]; V_c is critical velocity [m/s]; V_L is self-cleansing velocity [m/s]; g is acceleration due to gravity [m^2/s]; s is specific gravity for sediment and y is water depth [m]. May et al. [11] claimed (2) and (3) 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 [12]. For suspended load, (4) was plotted by Macke [13] with data from other studies [14-16].

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

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]; s is specific gravity for sediment and V_L is self-cleansing velocity [m/s]. Equation (4) is based on experiments for sediment diameter from 0.16 mm to 0.37 mm; pipe diameters of 192 mm, 290 mm and 445 mm; sediment concentrations from 3 ppm to 1700 ppm and is valid beyond bed shear stress of 1.07 N/m^2 [13].

B. With Limited Deposition Design Criteria

Compares to the design criteria without deposition mentioned earlier, design criteria with limited deposition gives less conservative design in terms of milder slope for both bed load and suspended load. This design criteria allows for small sediment deposition at the bottom of sewer, thus reduces the sewer slope. The presence of a limited depth of sediment deposit to the invert of the sewer reduced the slope requirement over entire range of sewer diameter [17]. However, this design criteria requires careful operation and maintenance of the sewer system since the condition is very close to critical condition.

A design chart such as the one shown in Figure 2 was developed by the Construction Industry Research and Information Association (CIRIA), UK based on the concept of non-deposition which incorporate the concept of limited deposition with allowable 2% of deposition depth. The design chart attempts to relate minimum velocity with the pipe size and roughness, proportional flow depth, sediment size and specific gravity, degree of cohesion between particles, sediment load or concentration and the presence of deposited bed [5]. The weakness of the CIRIA approach is that it is an envelope approach based on full pipe velocities and as such does not acknowledge actual design minimum flow rates [18].

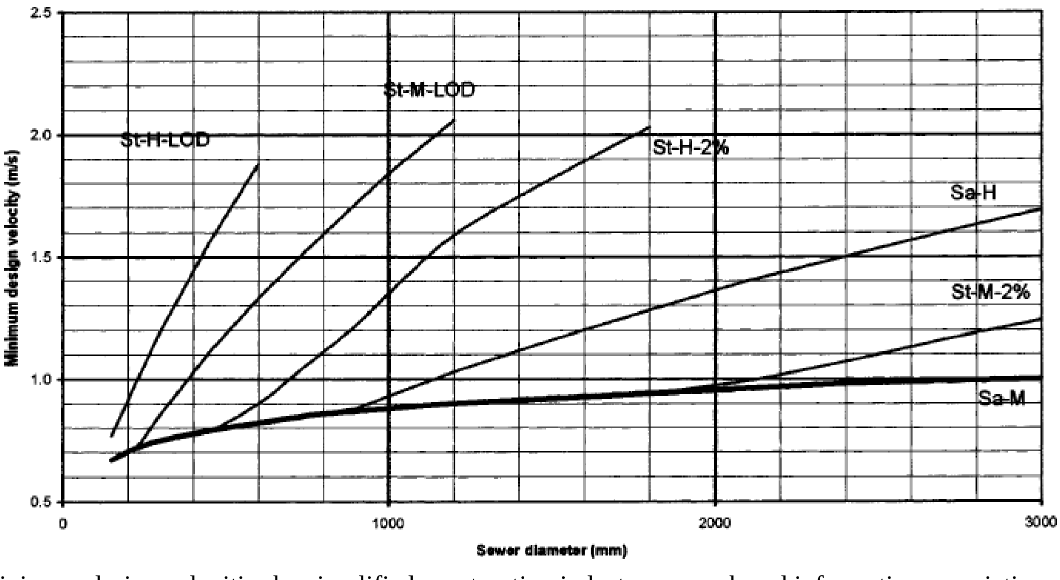

Figure 2 Minimum design velocities by simplified construction industry research and information association procedure. Sewer types: Sa = sanitary and St = storm; Sediment loads: M = medium, and H = high; Deposition criteria: LoD = limit-of-deposition and 2% = allowable deposition depth [5]

III. Design Concept Based on Moving of Existing Sediment on Sewer Bed

Under this design concept, further classification could be made into two groups; namely incipient motion and sediment transport. This design concept assumed that the sediment already deposited on sewer bed. The equations developed under this design concept take into account some aspect of sediment and channel characteristics so as to start moving the existing deposited sediment.

A. Moving of Existing Sediment on Sewer Bed Based on Incipient Motion

Recognizing that single minimum critical value criteria is not adequate for self-cleansing design, several researchers have studied incipient motion over rigid bed [19-23] and developed incipient motion equations that incorporate some aspect of sediment and channel characteristics. All the incipient motion equations developed by these researchers are in the form of:

$$\frac{V_c}{\sqrt{gd_{50}(s-1)}} a\left(\frac{d_{50}}{R}\right)^b \qquad (5)$$

where V_c is critical velocity [m/s]; g is acceleration due to gravity [m^2/s]; d_{50} is sediment median diameter [m]; s is specific gravity for sediment; R is hydraulic radius; a and b are coefficients. However, some existing literature for rigid bed channel has shown that the incipient motion equation in the form of (5) become less accurate as the sediment deposit thickness increased [24] due to changes in the hydraulic of the channel by the sediment deposits where the flow would assume a new depth above the deposited bed [25]. Thus, in recent development, the sediment deposit thickness has been suggested to be incorporated into (5) [26]. For very thick sediment deposition, the incipient motion condition is similar to that of loose boundary channel and (6) by Shields [27] could be used for self-cleansing design purposes.

$$\theta_c = \frac{\tau_c}{gd_{50}(\rho_s - \rho)} \qquad (6)$$

where θ_c is the dimensionless Shields stress; τ_c is the critical shear stress [N/m^2]; g is the acceleration due to gravity [m/s^2]; ρ_s is the sediment density [kg/m^3]; ρ is the fluid density [kg/m^3] and d_{50} is the sediment median diameter [m] [27].

B. Moving of Existing Sediment on Sewer Bed Based on Sediment Transport

As for the sediment transport design criteria, researchers have derived equations for velocity required to scour bed deposit on rigid beds [16, 19, 28]. Most of these sediment transport equations are in the form of:

$$\frac{V_s}{\sqrt{gd_{50}(s-1)}} = aC_v^b \qquad (7)$$

where V_s is scour velocity [m/s]; g is acceleration due to gravity [m^2/s]; d_{50} is sediment median diameter [m]; s is sediment specific gravity; C_v is sediment volumetric concentration [ppm]; a and b are coefficients.

IV. Design Concept Based on Energy Slope

In this design concept, the minimum sewer gradient S_0 is used as the criteria to avoid sediment deposition. This concept requires input parameters such as flow conditions, incoming sediment transport rate, sediment characteristics such as particle size and density; and hydraulic and pipe characteristics such as pipe geometry and hydraulic roughness [6]. Appropriate curves had been developed for calculating minimum sewer slope using tractive force design for self-cleansing [18] to be used for gravity sanitary sewer design in the United States as shown in Figure 3. A design chart relating the flow discharge with the sewer gradient and pipe diameter has been developed by Nalluri and Ab. Ghani [29] and as shown in Figure 4.

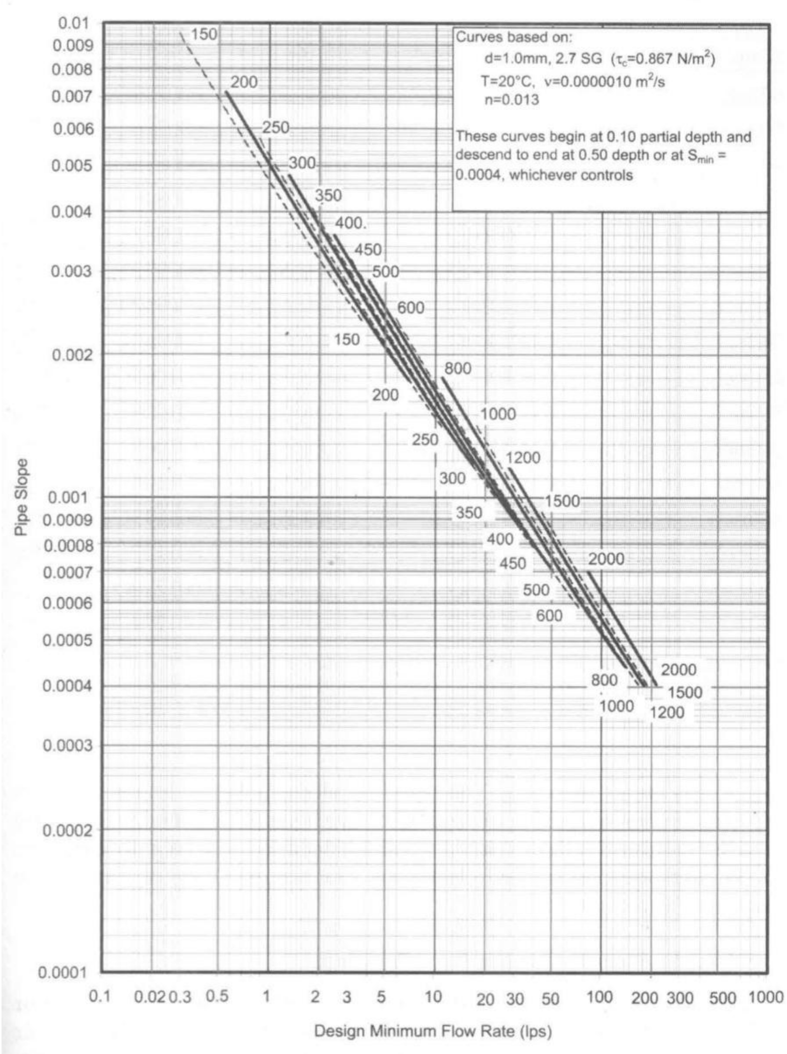

Figure 3 Self-cleansing slopes as a function of $Q_{\min}$ for Manning n = 0.013 [18]

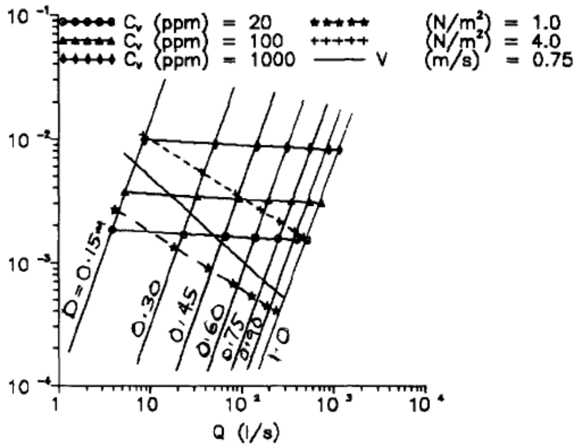

Figure 4 $Q - S_0 - D$ plot: clean pipe (half-full flow, d_{50} = 1.0 mm, k_0 = 0.6 mm) [29]

V. CLOSURE

Though a large number of researches and proposed criteria exist in the literature, many designers still prefer to use the adoption of a single minimum value of critical velocity or critical shear stress since these criteria are easy to use especially for a simple or small sewer system. A more viable approach for self-cleansing design is through the use of incipient motion equations which incorporate some aspect of the sediment and sewer characteristics. However, since most of the incipient motion equations were developed under controlled conditions in laboratory flumes; further studies are needed to better understand the representative particle size of sediment and sewer characteristics on-site. Experimental study for incipient motion of thicker sediment deposition could be conducted to determine at which sediment thickness the sewer bed will start to behave in similar manner to loose boundary bed. Moreover, little consistent data are available in the literature on sediment characteristics in developing countries that use open sewer system [30]. Therefore, further studies are encouraged on aforementioned cases so as to provide valuable information to improve the existing self-cleaning design criteria for sewer.

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