Velocity-based analysis of sediment incipient deposition in rigid boundary open channels

Hafzullah Aksoy, Mir Jafar Sadegh Safari, Necati Erdem Unal and Mirali Mohammadi

ABSTRACT

Drainage systems must be designed in a way to minimize undesired problems such as decrease in hydraulic capacity of the channel, blockage and transport of pollutants due to deposition of sediment. Channel design considering self-cleansing criteria are used to solve the sedimentation problem. Incipient deposition is one of the non-deposition self-cleansing design criteria that can be used as a conservative method for channel design. Experimental studies have been carried out in five different cross-section channels, namely trapezoidal, rectangular, circular, U-shape and V-bottom. Experiments were performed in a tilting flume using four different sizes of sands as sediment in nine different channel bed slopes. Two well-known methods, namely the Novak & Nalluri and Yang methods are considered for the analysis of sediment motion. Equations developed using experimental data are found to be in agreement with the literature. It is concluded that the design velocity depends on the shape of the channel cross-section. Rectangular and V-bottom channels need lower and higher incipient deposition velocities, respectively, in comparison with other channels.

Key words | drainage system, incipient deposition, rigid boundary channel, sediment transport, self-cleansing

Hafzullah Aksoy (corresponding author)
Necati Erdem Unal
Department of Civil Engineering,
Istanbul Technical University,
Istanbul,
Turkey
E-mail: *haksoy@itu.edu.tr*

Mir Jafar Sadegh Safari
Mirali Mohammadi
Department of Civil Engineering,
Urmia University,
Urmia,
Iran

Mir Jafar Sadegh Safari
Department of Civil Engineering,
University of Tabriz,
Tabriz,
Iran

INTRODUCTION

Continuous deposition of sediment in drainage systems causes numerous undesired problems. It influences the environment by transporting pollution and overflowing pollutant water to be spread over urban areas. At the same time, it reduces the hydraulic capacity of the channel by decreasing the flow cross-section area. The aforesaid problems have adverse effects on the performance and efficiency of drainage systems. Additional costs arise to keep the system at its design performance.

A reasonable solution to prevent such problems is the design of drainage systems considering self-cleansing criteria: (i) sediment particles at the channel bottom start to move (Bong *et al.* 2013, 2016); (ii) sediment particles moving within the flow are transported without being deposited (May *et al.* 1996, Butler *et al.* 2003; Safari *et al.* 2017). The second criterion is mostly used for drainage system design. It covers three conditions: (a) non-deposition without deposited bed, (b) non-deposition with deposited bed, and (c) incipient deposition. The non-deposition without deposited bed condition is used for preventing deposition of sediment, which keeps the channel bottom clean (Mayerle *et al.* 1991; Ab Ghani 1993; May 1993; Ackers *et al.* 1996; May *et al.* 1996; Ota & Nalluri 2003; Vongvisessomjai *et al.* 2010; Ota & Perrusquia 2013; Safari *et al.* 2017). It is suitable for small drainage systems (circular channels with diameter less than 500 mm) as it is more conservative to give a steeper channel bed slope for large sewers (Ab Ghani 1993; Ackers *et al.* 1996). To this extent, the non-deposition with deposited bed criterion is adapted for designing large sewers in which a small portion of deposited bed exists at the channel bottom. This reduces the design channel bed slope considerably without a significant effect on the transport capacity of the channel (Ackers 1991; El-Zaemey 1991; Ab Ghani 1993; May 1993; Nalluri *et al.* 1994, 1997; Perrusquia & Nalluri 1995; Nalluri & Ab Ghani 1996). However, it needs careful operation as flow is close to the critical deposition condition. Incipient deposition is defined as the condition in which sediment particles in suspension start to deposit. They are transported as bed load or accumulated at the channel bottom

doi: 10.2166/wst.2017.429

without making a deposited bed layer (Loveless 1992; Safari et al. 2015, 2016).

Incipient deposition was firstly investigated by Loveless (1992) in several cross-section channels, namely rectangular, circular, U-shape and oval. As it was in ASCE Task Force (1966), Loveless (1992) assumed that incipient motion and incipient deposition are similar to each other with a questionable slight difference. Experimental data of Loveless (1992) fit the models of May (1982) and Ackers (1984) acceptably. Safari et al. (2014, 2015) studied incipient deposition of sediment particles in rigid boundary channels considering the effect of the channel cross-section by using the experimental data of Loveless (1992). It is concluded that incipient deposition velocity is higher than that of incipient motion under the same flow conditions for non-cohesive sediment whereas, in the case of cohesive particles, the velocity needed to set the particles in motion is considerably higher than the velocity at which the movement ceased (Butler et al. 1996). The results denied the common assumption that incipient deposition and incipient motion are the same. Safari et al. (2015) re-analyzed the experimental data of Loveless (1992) and developed incipient deposition models using the method proposed by Graf & Acaroglu (1968) to propose a set of practical formulae for channel design. The two related concepts, incipient deposition and incipient motion, were distinguished using the available data in the literature. In order to explain the exact difference between incipient deposition and incipient motion, Aksoy & Safari (2014) performed a preliminary study on incipient motion and incipient deposition in a trapezoidal cross-section channel. As a result, it was found that the threshold condition has a wider range between higher and lower boundaries; incipient deposition where particles in motion tend to deposit and incipient motion where stationary particles tend to move. In order to achieve more conclusive results, conducting a new set of experiments with a wider range of sediment sizes in different channel cross-sections seems to be valuable.

As highlighted above, there are very few studies on incipient deposition of sediment in rigid boundary channels. Examination of incipient deposition by evaluating sediment motion under laboratory conditions with consideration of shear stress, velocity, channel cross-section, particle size, settling velocity of particles, and other boundary conditions becomes vital. To this extent, this study experimentally investigates incipient deposition of sediment in five different cross-section channels, namely trapezoidal, rectangular, circular, U-shape and V-bottom. This has been done through use of two well-known velocity-based methods, the Novak & Nalluri and Yang methods.

EXPERIMENTAL DATA

Experiments were carried out in the Hydraulic Laboratory, Civil Engineering Faculty of Istanbul Technical University (Safari 2016; Unal et al. 2016). Experiments were conducted in five channels. Made of the transparent thermoplastic also known as acrylic or acrylic glass (Plexiglas), each channel is 12 m long. Trapezoidal, rectangular, circular, U-shape and V-bottom cross-sections were used. The channels were mounted on an iron-made support structure. As shown in Figure 1,

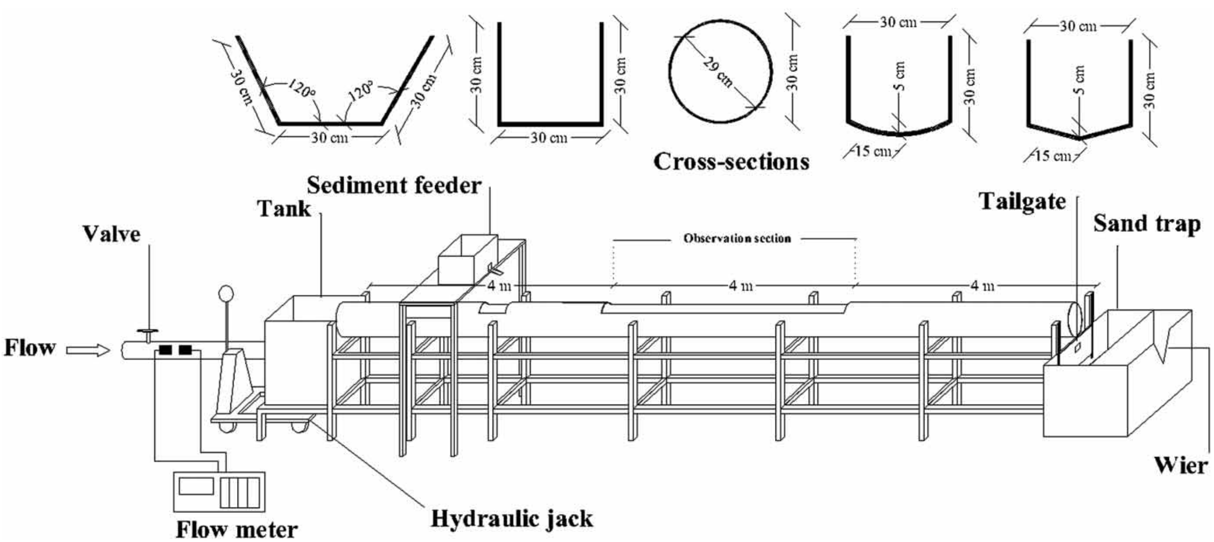

Figure 1 | Experimental apparatus and channel cross-sections.

all cross-sections have a width of 300 mm, approximately. The rectangular, U-shape and V-bottom cross-sections have a surface width of 300 mm, while the trapezoidal channel has the same width at the bottom. The circular cross-section has an inner diameter of 290 mm. The cross-fall in the U-shape and V-bottom cross-sections is 50 mm. The trapezoidal cross-section has an outer angle of 60° at the 30 cm-long side wall.

Experiments were repeated for nine channel bed slopes changing from 0.00147 to 0.01106. As sediment, four sizes of uniform non-cohesive sands were used. The granulometry curves of sands are given in Figure 2. Characteristics of the sediment used in the experiments are shown in Table 1, in which d_{50} is the median diameter, s the mass density and σ_g the geometric standard deviation of the particle size distribution. For each experiment, discharge was measured by an ultrasonic flow-meter. Sediment motion was observed throughout each experiment. Observation was made in the 4 m-long section of the channel, located 4 m from the upstream and 4 m from the downstream. Observations and measurements were done under uniform flow conditions.

Experiments start with such a flow condition that velocity is high enough to prevent the deposition of sediment particles. A non-deposition sediment transport condition is achieved by adjusting the flow discharge. In this condition, discharge is high enough to prevent sediment deposition; sediment particles within the flow are transported. Incipient deposition can be achieved by reducing the flow velocity. A gradual decrease in the discharge allows the flow to switch from non-deposition to incipient deposition. The flow condition in which sediment particles begin to deposit is called incipient deposition. As used by Loveless (1992), in the experiments, incipient deposition was identified as the sediment transport mode in which sediment particles were clustered visibly in certain areas at the bottom of the channel. In this case, flow velocity is sufficiently low for incipient deposition of sediment. Incipient deposition in trapezoidal and rectangular channels has similar forms. However, in U-shape and V-bottom channels, sediment particles were deposited in the center line of the channel. The form of deposition was dependent on the shape of the channel bed. In the V-bottom channel, which has a narrow center line, sediment particles accumulated on each other, while accumulation in the circular and U-shape channels is not, due to the wider bed formed along the centerline width they have. Sediment particles spread over the bed width to make a deposited sediment layer.

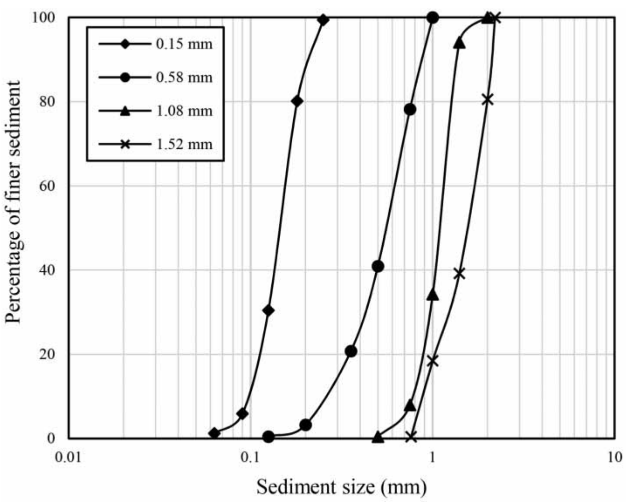

Figure 2 | Sediment granulometry.

Table 1 | Characteristics of sediment used in experiments

d_{50} (mm)	0.15	0.58	1.08	1.52
S	2.60	2.63	2.56	2.60
σ_g	1.3	1.6	1.3	1.4

EXPERIMENTAL DATA ANALYSIS

Methods proposed by Novak & Nalluri (1984) and Yang (1973) are used for analyzing incipient deposition experimental data. The methods are named N-N and Yang, respectively. The methods and analysis are given in the following sections.

N-N method

Through theoretical consideration, sediment particles at the channel bed move in the flow, while drag and lift forces dominate the buoyed weight of sediment and the resistance force. The aforementioned forces are calculated by

$$F_d = \frac{\pi}{8} c_d \rho d^2 u_b^2 \quad (1)$$

$$F_l = \frac{\pi}{8} c_l \rho d^2 u_b^2 \quad (2)$$

$$F_g = \frac{\pi}{6} d^3 (\rho_s - \rho) g \quad (3)$$

$$F_r = k(F_g - F_l) \tag{4}$$

where F_d, F_l, F_g, F_r are the drag force, the lift force, the buoyed weight of sediment, and the resistance force, respectively; c_d and c_l are the drag and lift coefficients, respectively; ρ and ρ_s are fluid and sediment specific masses, respectively; d is sediment median diameter, u_b is near bed flow velocity, g is gravitational acceleration, and k is the Coulomb friction coefficient. The drag force should be equal to the resistance force in the sediment threshold condition. Therefore,

$$F_d = k(F_g - F_l). \tag{5}$$

Substituting Equations (1)–(4) into Equation (5) gives

$$\frac{u_b}{\sqrt{gd(s-1)}} = \sqrt{\frac{4}{3}\frac{k}{c_d + kc_l}}. \tag{6}$$

According to Novak & Nalluri (1975, 1984), Equation (6) can be simplified as

$$Fr_{id} = \frac{V_{id}}{\sqrt{gd(s-1)}} = a\left(\frac{d}{R}\right)^b \tag{7}$$

in which relative particle size (d/R where R is hydraulic radius) is used. In order to make a practical engineering tool for channel design, in Equation (7) flow mean velocity (V_{id}) is used instead of near bed flow velocity. The left hand side of Equation (7) is incipient deposition particle Froude number (Fr_{id}). Safari et al. (2014), who applied Equation (7) on the experimental data of Loveless (1992), proposed

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 0.48\left(\frac{d}{R}\right)^{-0.70} \tag{8}$$

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 0.62\left(\frac{d}{R}\right)^{-0.64} \tag{9}$$

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 0.92\left(\frac{d}{R}\right)^{-0.55} \tag{10}$$

for rectangular, circular and U-shape channels, respectively. Safari et al. (2015) generalized the above equations for any channel cross-section as

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 0.72\left(\frac{d}{R}\right)^{-0.60}. \tag{11}$$

As presented above, the dimensionless particle Froude number (Fr_{id}) and relative particle size (d/R) are used for developing incipient deposition relationships. Utilizing the experimental data of this study

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 1.28\left(\frac{d}{R}\right)^{-0.44}, \ 0.01 < \frac{d}{R} < 0.15 \tag{12}$$

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 0.86\left(\frac{d}{R}\right)^{-0.45}, \ 0.01 < \frac{d}{R} < 0.18 \tag{13}$$

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 1.14\left(\frac{d}{R}\right)^{-0.44}, \ 0.01 < \frac{d}{R} < 0.09 \tag{14}$$

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 1.35\left(\frac{d}{R}\right)^{-0.41}, \ 0.01 < \frac{d}{R} < 0.08 \tag{15}$$

$$\frac{V_{id}}{\sqrt{gd(s-1)}} = 1.28\left(\frac{d}{R}\right)^{-0.43}, \ 0.01 < \frac{d}{R} < 0.09 \tag{16}$$

are obtained for trapezoidal, rectangular, circular, U-shape and V-bottom cross-section channels, respectively for given ranges of relative particle sizes. Comparison of Equations (12)–(16) with their corresponding experimental data are shown in Figure 3. It is seen that among different cross-section channels, the rectangular channel needs the lowest incipient deposition velocity in comparison with other cross-section channels. V-bottom and U-shape channels require higher incipient deposition velocity. Trapezoidal and circular channel data remained between U-shape and rectangular channel data. However, the circular channel needs slightly lower incipient deposition velocity in comparison with the trapezoidal channel.

Incipient deposition experimental data obtained in this study for rectangular, circular and U-shape channels are compared with corresponding data of Loveless (1992) in Figures 4–6. Data from this study are found to be close to the experimental data of Loveless (1992); thus Equation (13) proposed for the rectangular channel in this study is near to Equation (8) developed on Loveless (1992) rectangular channel data for $0.02 < d/R < 0.10$. It should be noticed, the smallest sediment particle size used by Loveless (1992) had a median size of 0.45 mm. In this study, fine sand with median size of 0.15 mm is used as the smallest particle size. This study provides data for smaller d/R. It is found from Figures 5 and 6

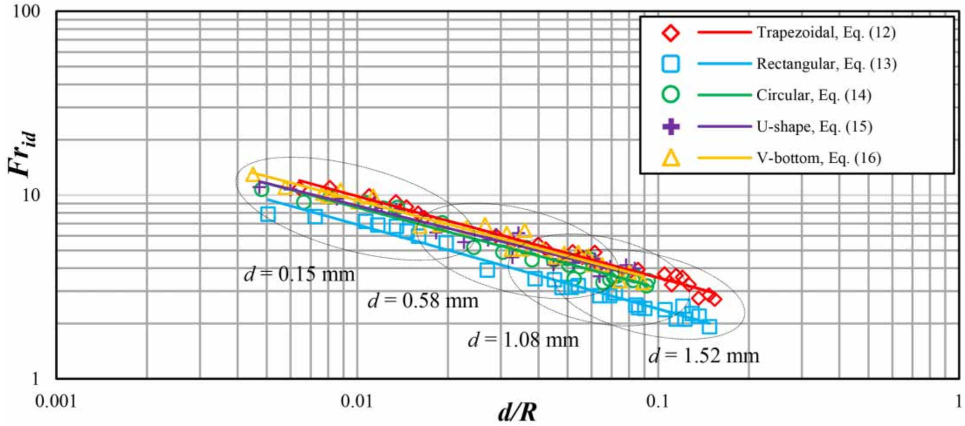

Figure 3 | Incipient deposition equations based on N-N method.

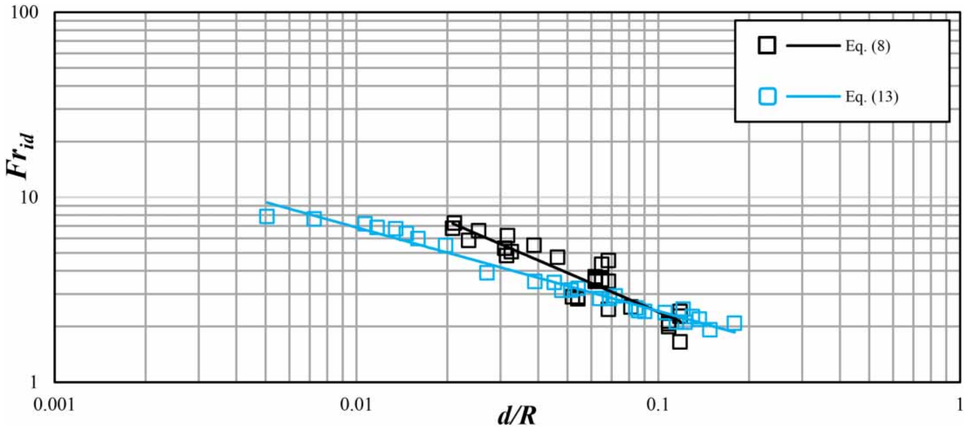

Figure 4 | Incipient deposition equations based on N-N method for rectangular channel.

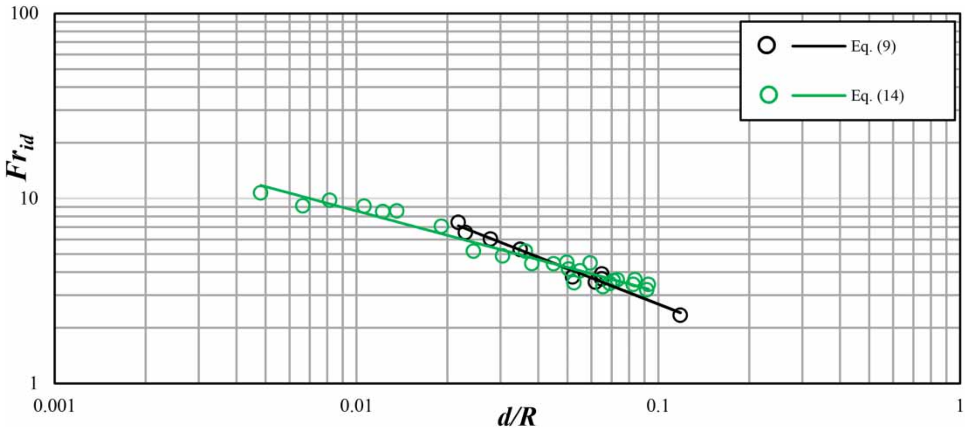

Figure 5 | Incipient deposition equations based on N-N method for circular channel.

that circular and U-shape channel incipient deposition experimental data of this study match quite well with the corresponding data of Loveless (1992), who used sediment with a median size of 6 mm in a U-shape channel. Hence, as it is shown in Figure 6, Loveless (1992) provided data for $d/R > 0.1$.

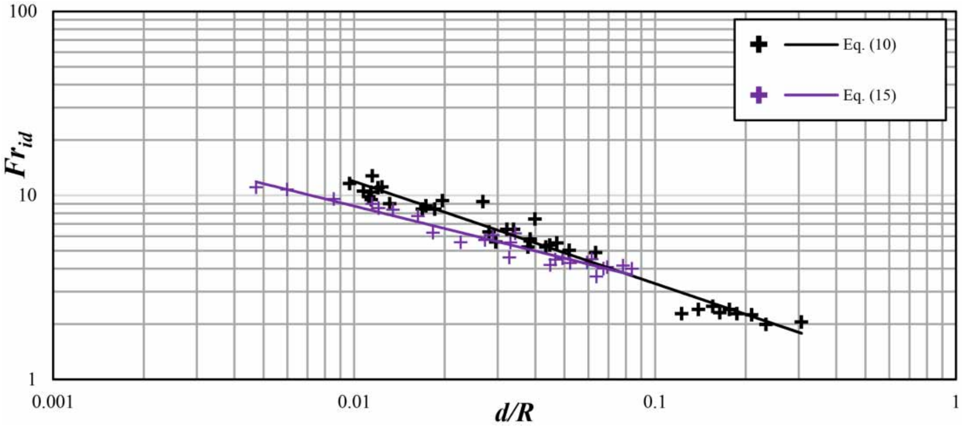

Figure 6 | Incipient deposition equations based on N-N method for U-shape channel.

Results obtained in this study tend to support the findings of Loveless (1992), confirmed also by Safari *et al.* (2014). The U-shape channel needed higher incipient deposition velocity than the rectangular and circular channels. It is an important point to mention that rectangular, circular and U-shape channels in Loveless (1992) differ from each other in size, while each channel in this study has a width of 300 mm approximately. Therefore, it can be said that this study provides more conclusive results in terms of the effect of channel cross-section shape on the incipient deposition of sediment within flow.

Yang method

Yang (1973) proposed a method in which the settling velocity of a sediment particle is taken into account. Yang (1973) also indicated that the terminal settling velocity of a sediment particle is reached when there is a balance between the drag force generated by the sediment particle as it falls and its buoyed weight given by

$$\frac{\pi}{8}c'_d\rho d^2w^2 = \frac{\pi}{6}d^3(\rho_s-\rho)g \tag{17}$$

in which w is the settling velocity of sediment particle and c'_d is the drag coefficient at w. Assuming $c'_d = \alpha_1 c_d$ (α_1 is a constant) and substituting Equation (1) into Equation (17) gives

$$F_D = \frac{\pi g d^3}{6\alpha_1 w^2}(\rho_s-\rho)u_b^2. \tag{18}$$

Applying logarithmic law for velocity distribution and using flow mean velocity (V_{id}) instead of u_b by integrating velocity distribution, a logarithmic relationship (Yang 1973)

$$F_D = \frac{\pi g d^3}{6\alpha_1}(\rho_s-\rho)\left(\frac{V_{id}}{w}\right)^2\left[\frac{B}{5.75(\log(Y/d)-1)+B}\right]^2 \tag{19}$$

is obtained in which B is the roughness function and Y is flow depth. Considering the lift force (F_l) and assuming $c_d = \alpha_2 c_l$ (α_2 is a constant) and following the same procedure as in Equation (19)

$$F_l = \frac{\pi g d^3}{6\alpha_1\alpha_2}(\rho_s-\rho)\left(\frac{V_{id}}{w}\right)^2\left[\frac{B}{5.75(\log(Y/d)-1)+B}\right]^2 \tag{20}$$

is achieved. Substituting Equations (3) and (20) into the resistance force relationship (Equation (4)) gives

$$F_r = \frac{k\pi g d^3}{6}(\rho_s-\rho)\left\{1-\frac{1}{\alpha_1\alpha_2}\left(\frac{V_{id}}{w}\right)^2\left[\frac{B}{5.75(\log(Y/d)-1)+B}\right]^2\right\}. \tag{21}$$

At the threshold condition, the drag force should be equal to the resistance force; thus from Equations (19) and (21)

$$\frac{V_{id}}{w} = \left[\frac{5.75(\log(Y/d)-1)}{B}+1\right]\sqrt{\frac{\alpha_1\alpha_2 k}{\alpha_2+k}} \tag{22}$$

is obtained. Yang (1973) indicated that in hydro-dynamically smooth and transition regions with $Re^* = u^*d/\nu < 70$, B is given as a function of particle Reynolds number by

$$B = 5.5 + 5.75\log(u^*d/\nu) \tag{23}$$

where v is the kinematic viscosity of fluid and u^* is shear velocity, calculated by

$$u^* = \sqrt{\frac{\tau}{\rho}} \tag{24}$$

where τ is the average bed shear stress. Substituting Equation (23) into Equation (22) gives

$$\frac{V_{id}}{w} = \left[\frac{(\log(Y/d) - 1)}{\log(u^*d/\upsilon) + 0.956} + 1\right]\sqrt{\frac{\alpha_1\alpha_2 k}{\alpha_2 + k}} \tag{25}$$

that is a hyperbolic function between V_{id}/w and u^*d/v. In the rough region, laminar friction contribution is neglected and B takes a constant value of 8.5 (Yang 1973). Thus, Equation (22) turns into

$$\frac{V_{id}}{w} = \left[\frac{(\log(Y/d) - 1)}{1.48} + 1\right]\sqrt{\frac{\alpha_1\alpha_2 k}{\alpha_2 + k}} \tag{26}$$

which is a straight horizontal line when V_{id}/w is plotted against u^*d/v. Using experimental data, Yang (1973) quantified coefficients to develop the final form of Equations (25)–(26) as

$$\frac{V_{id}}{w} = \left[\frac{2.5}{\log(u^*d/\upsilon) - 0.06} + 0.66\right], \quad 1.2 < \frac{u^*d}{\upsilon} < 70 \tag{27}$$

$$\frac{V_{id}}{w} = 2.05, \quad \frac{u^*d}{\upsilon} > 70 \tag{28}$$

In this study, the methodology of Yang (1973) was used to develop

$$\frac{V_{id}}{w} = \frac{81.62}{\log(u^*d/\upsilon) + 3.96} - 12.92, \ 3.13 < \frac{u^*d}{\upsilon} < 47.61 \tag{29}$$

$$\frac{V_{id}}{w} = \frac{3.56}{\log(u^*d/\upsilon) + 0.33} - 0.69, \ 2.36 < \frac{u^*d}{\upsilon} < 29.89 \tag{30}$$

$$\frac{V_{id}}{w} = \frac{4.47}{\log(u^*d/\upsilon) + 0.29} - 0.47, \ 3.02 < \frac{u^*d}{\upsilon} < 41.11 \tag{31}$$

$$\frac{V_{id}}{w} = \frac{23.79}{\log(u^*d/\upsilon) + 2.02} - 4.17, \ 3.19 < \frac{u^*d}{\upsilon} < 48.11 \tag{32}$$

$$\frac{V_{id}}{w} = \frac{32.29}{\log(u^*d/\upsilon) + 1.97} - 6.82, \ 3.46 < \frac{u^*d}{\upsilon} < 52.69 \tag{33}$$

for incipient deposition of sediment in trapezoidal, rectangular, circular, U-shape and V-bottom channels, respectively, for given ranges of particle Reynolds numbers in which the settling velocity of sediment particles (w) within turbulent flow is computed by

$$w = \sqrt{3.3gd(s-1)}. \tag{34}$$

As mentioned before, the Yang diagram is composed of two parts; a hyperbolic part and a constant part. Particle Reynolds numbers of experimental data in this study are found in the range of $1.2 < u^*d/\upsilon < 70$ for which the hyperbolic part is applied. Therefore Equations (29)–(33) were developed in hyperbolic form in this study.

Comparison of Equations (29)–(33) in Figure 7 indicates that incipient deposition experimental data of trapezoidal, circular, U-shape, and V-bottom channels fit quite well to the Yang curve, while circular channel data are slightly below the Yang curve. It can be said that the required incipient deposition velocity in rigid boundary channels with trapezoidal, circular, U-shape, and V-bottom channels is approximately equal to the incipient motion velocity in loose boundary channels when the Yang method is considered. The rectangular channel requires lower incipient deposition velocity among the five different cross-section channels.

As presented before, the non-deposition design is based on three criteria: non-deposition without deposited bed, non-deposition with deposited bed, and incipient deposition. Among these, incipient deposition is less conservative than non-deposition without deposited bed and more conservative than the non-deposition with deposited bed criteria. The former is applied for small sewers, while the latter is used for large sewers. Therefore, it may be concluded that incipient deposition can be used for the design of medium size drainage systems, as there is sediment accumulated in some parts of the channel bed without making a deposited bed layer. However, in non-deposition without deposited bed, the channel has no deposited bed. This case may be observed in longitudinally steep channels. For the case of non-deposition with deposited bed, sediment particles are transported at the bed surface at the bottom of the channel. Consequently, it can be said that the incipient deposition can be considered as a design criterion between the two common design criteria; non-deposition with and without deposited bed.

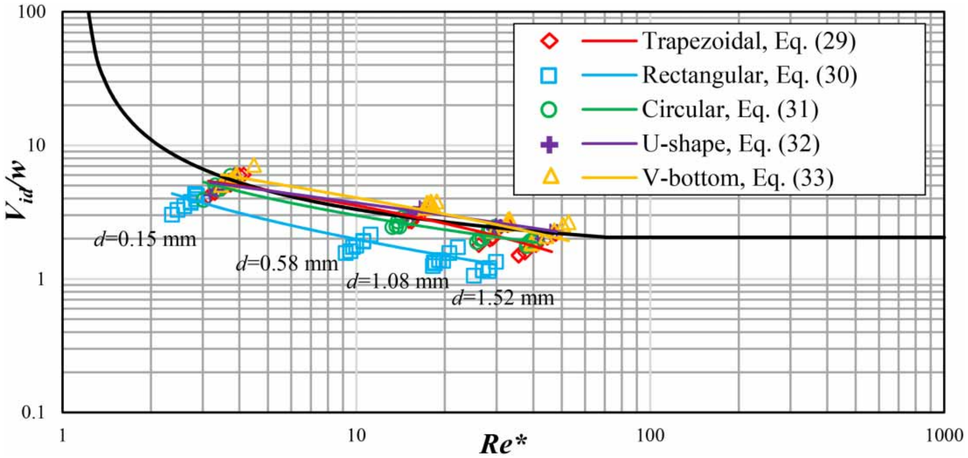

Figure 7 | Incipient deposition equations based on Yang method.

Results indicate that the velocity required for incipient deposition of sediment depends on the channel cross-section. This can be linked to the fact that velocity distribution in open channels is non-uniform over the cross-section. This study provides a practical tool based on the mean flow velocity to use for the channel design.

CONCLUSION

Incipient deposition of sediment in five different cross-section channels, namely trapezoidal, rectangular, circular, U-shape and V-bottom, is investigated experimentally. Two well-known methods, Novak & Nalluri (1984) and Yang (1973), are considered for calculating flow velocity under the incipient deposition condition. When the method of Novak & Nalluri (1984) is considered, experimental data are found in a good agreement with the corresponding data available in the literature. Among the five channels, the rectangular channel provides the lowest incipient deposition velocity. This indicates the effect of the channel cross-section on the incipient deposition. Based on the findings of this study, the Yang (1973) method, originally proposed for loose boundary channels, can be successfully used for modeling sediment transport in rigid boundary channels as the incipient deposition data in this study are found to be close to the Yang curve. Hence, it can be said that the incipient deposition velocity in rigid boundary channels is close to its counterpart in loose boundary channels.

Despite the positive achievement, it should be mentioned that incipient deposition experimental data used in this study is for relatively fine sediment. For further exploration, new sets of experiments using coarser sediment particle size would be useful for extrapolation of the equations.

ACKNOWLEDGEMENTS

This study was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under the project 114M283. The study has also received partial support from the Scientific Research Projects (BAP) Unit of Istanbul Technical University under the project 37973.

REFERENCES

Ab Ghani, A. 1993 *Sediment Transport in Sewers*. PhD Thesis, University of Newcastle upon Tyne.

Ackers, P. 1984 Sediment transport in sewers and 654 the design implications. In: *Intern. Conf. on Planning, Construction, Maintenance, and Operation of Sewerage Systems, BHRA/WRc*, Reading, UK, pp. 215–230.

Ackers, P. 1991 Sediment aspects of drainage and outfall design. In: *Proc. Int. Symposium on Environmental Hydraulics*, Hong Kong.

Ackers, J. C., Butler, D. & May, R. W. P. 1996 *Design of Sewers to Control Sediment Problems*. Construction Industry Research and Information Association (CIRIA) Rep. No. 141, London, pp. 1–181.

Aksoy, H. & Safari, M. J. S. 2014 *Incipient Deposition of Sediment Particles in Rigid Boundary Channels*. TÜBİTAK, the Scientific and Technological Research Council of Turkey, Project Report, 113M062, May 2014, Istanbul (in Turkish).

ASCE Task Force on Sediment Transportation Mechanics 1966 Incipient of motion. *J. Hydraul. Div. ASCE* **92** (HY2), 291–314.

Bong, C. H. J., Lau, T. L. & Ab Ghani, A. 2013 Verification of equations for incipient motion studies for a rigid rectangular channel. *Water Science and Technology* **67** (2), 395–403.
Bong, C. H. J., Lau, T. L., Ab Ghani, A. & Chan, N. W. 2016 Sediment deposit thickness and its effect on critical velocity for incipient motion. *Water Science and Technology* **74** (8), 1876–1884.
Butler, D., May, R. W. P. & Ackers, J. C. 1996 Sediment transport in sewers. Pt. 1: background. *P. I. Civil. Eng.-Mar. Eng.* **118** (2), 103–112.
Butler, D., May, R. & Ackers, J. 2003 Self-cleansing sewer design based on sediment transport principles. *J. Hydraul. Eng.* **129** (4), 276–282.
El-Zaemey, A. K. S. 1991 *Sediment Transport Over Deposited Beds in Sewers*. PhD Thesis, University of Newcastle upon Tyne.
Graf, W. H. & Acaroglu, E. R. 1968 Sediment transport in conveyance systems, Part 1: a physical model for sediment transport in conveyance systems. *Hydrological Sciences Journal* **13** (2), 20–39.
Loveless, J. H. 1992 *Sediment Transport in Rigid Boundary Channels with Particular Reference to the Condition of Incipient Deposition*. PhD Thesis, University of London.
May, R. W. P. 1982 *Sediment Transport in Sewers*. Report No. IT 222, Hydraulic Research Station, Wallingford, UK.
May, R. W. P. 1993 *Sediment Transport in Pipes and Sewers with Deposited Beds*. Technical Report, Hydraulic Research Ltd, Report SR 320, Wallingford, UK.
May, R. W., Ackers, J. C., Butler, D. & John, S. 1996 Development of design methodology for self-cleansing sewers. *Water Science and Technology* **33** (9), 195–205.
Mayerle, R., Nalluri, C. & Novak, P. 1991 Sediment transport in rigid bed conveyances. *J. Hydraul. Res.* **29** (4), 475–495.
Nalluri, C. & Ab Ghani, A. 1996 Design options for self-cleansing storm sewers. *Water Science and Technology* **33** (9), 215–220.
Nalluri, C., Ab Ghani, A. & El-Zaemey, A. K. S. 1994 Sediment transport over deposited beds in sewers. *Water Science and Technology* **29** (1–2), 125–133.
Nalluri, C., El-Zaemey, A. K. & Chan, H. L. 1997 Sediment transport over fixed deposited beds in sewers-an appraisal of existing models. *Water Science and Technology* **36** (8), 123–128.
Novak, P. & Nalluri, C. 1975 Sediment transport in smooth fixed bed channels. *J. Hydraul. Div. ASCE* **101** (HY9), 1139–1154.
Novak, P. & Nalluri, C. 1984 Incipient motion of sediment particles over fixed beds. *J. Hydraul. Res.* **22** (3), 181–197.
Ota, J. J. & Nalluri, C. 2003 Urban storm sewer design: approach in consideration of sediments. *J. Hydraul. Eng. ASCE* **129** (4), 291–297.
Ota, J. J. & Perrusquia, G. S. 2013 Particle velocity and sediment transport at the limit of deposition in sewers. *Water Science and Technology* **67** (5), 959–967.
Perrusquia, G. S. & Nalluri, C. 1995 Modelling of bed-load transport in pipe channels. In: *International Conference on the Transport and Sedimentation of Solid Particles*, Prague.
Safari, M. J. S. 2016 *Self-cleansing Drainage System Design by Incipient Motion and Incipient Deposition-based Models*. PhD Thesis, Istanbul Technical University, Turkey.
Safari, M. J. S., Mohammadi, M. & Gilanizadehdizaj, G. 2014 On the effect of cross sectional shape on incipient motion and deposition of sediments in fixed bed channels. *J. Hydrol. Hydromech.* **62** (1), 75–81.
Safari, M. J. S., Aksoy, H. & Mohammadi, M. 2015 Incipient deposition of sediment in rigid boundary open channels. *Environ. Fluid Mech.* **15** (5), 1053–1068.
Safari, M. J. S., Aksoy, H. & Mohammadi, M. 2016 Artificial neural network and regression models for flow velocity at sediment incipient deposition. *J. Hydrol.* **541**, 420–1429.
Safari, M. J. S., Aksoy, H., Unal, N. E. & Mohammadi, M. 2017 Non-deposition self- cleansing design criteria for drainage systems. *J. Hydro-Environ. Res.* **14**, 76–84.
Unal, N. E., Aksoy, H. & Safari, M. J. S. 2016 *Self-cleansing Drainage System Design by Incipient Motion and Incipient Deposition-based Models*. TÜBİTAK, the Scientific and Technological Research Council of Turkey, Project Report, 114M283, November 2016, Istanbul (in Turkish).
Vongvisessomjai, N., Tingsanchali, T. & Babel, M. S. 2010 Non-deposition design criteria for sewers with part-full flow. *Urban Water J.* **7** (1), 61–77.
Yang, C. T. 1973 Incipient motion and sediment transport. *J. Hydraul. Div. ASCE* **99** (10), 1679–1704.

First received 9 May 2017; accepted in revised form 4 July 2017. Available online 19 July 2017