Jurnal
Teknologi

Full Paper

DEPOSITION THICKNESS AND ITS EFFECT ON CRITICAL SHEAR STRESS FOR INCIPIENT MOTION OF SEDIMENTS

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Article history
Received
4 March 2016
Received in revised form
15 May 2016
Accepted
25 May 2016

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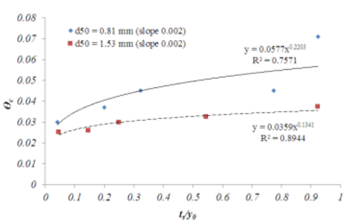
Graphical abstract



Abstract

There are evidences in existing literatures suggesting the incipient motion values for any particle size is substantially lower for rigid boundary condition as compared to loose boundary condition. The objective of the current study is to determine the effect of sediment deposition thickness on the critical shear stress for incipient motion. Experimental works for incipient motion were carried out in a rectangular flume with varying sediment deposits thickness. Results showed that the sediment deposits thickness has effect on the critical shear stress at low sediment deposits thickness and the effect will slowly diminish as the sediment deposits thickness increases. Multiple linear regression analysis was performed on the experimental data to develop a new critical shear stress equation. The best regression model has R^2 value of 0.69; R^2_{adj} value of 0.60; MSE value of 0.009 and Mallow's C_p value of 3.00. The new equation appears to be more consistent as compared to existing incipient motion equations for rigid boundary condition by having 80% of the predicted data falls within the acceptable discrepancy ratio when tested with data from other authors. The new equation can be used to determine critical shear stress values for self-cleansing sewerage design and other related engineering applications.

Keywords: Critical shear stress; incipient motion; loose boundary; rigid boundary; sediment

Abstrak

Terdapat bukti di dalam literatur sedia ada yang menunjukkan bahawa pergerakan ambang berlaku pada tegasan ricih kritikal yang lebih rendah untuk saluran bersempadan tegar jika dibandingkan dengan saluran bersempadan longgar. Objektif kajian ini dijalankan adalah untuk memahami kesan ketebalan kelodak kepada tegasan ricih kritikal. Eksperimen untuk pergerakan ambang telah dijalankan di dalam saluran tegar segiempat dengan mengubah ketebalan kelodak. Keputusan eksperimen menunjukkan bahawa kesan ketebalan kelodak kepada tegasan ricih kritikal adalah ketara pada ketebalan rendah dan kesan ini akan beransur kurang apabila ketebalan kelodak meningkat. Data daripada eksperimen digunakan untuk menerbitkan persamaan tegasan ricih kritikal baru menggunakan analisis regresi linear berganda. Model regresi terbaik mempunyai nilai R^2 bersamaan 0.69; nilai R^2_{adj} bersamaan 0.60; nilai MSE bersamaan 0.009 dan nilai Mallow's C_p bersamaan 3.00 Persamaan baru ini adalah lebih konsisten apabila dibandingkan dengan persamaan tegasan ricih kritikal untuk saluran bersempadan tegar yang sedia ada dalam literatur dengan 80% daripada data oleh pengkaji-pengkaji lain yang diramal jatuh di dalam lingkungan nisbah percanggahan yang boleh diterima. Persamaan baru ini boleh digunakan untuk menentukan nilai tegasan ricih kritikal untuk tujuan rekabentuk cuci diri pembetungan dan lain-lain aplikasi kejuruteraan berkenaan.

Kata kunci: Kelodak; pergerakan ambang; sempadan longgar; sempadan tegar; tegasan ricih kritikal

1.0 INTRODUCTION

The condition that is just adequate to initiate sediment motion is termed critical condition while the initial motion of sediment particles is commonly called incipient motion [1]. Though there exist enormous literatures on incipient motion, the majority of the literatures were for loose boundary channel (with unlimited sediment depth and supply) as compared to rigid boundary channel (with limited sediment depth and supply)[2, 3]. For the purpose of engineering design such as for stable channel, the Shields diagram [4] was conventionally used to predict incipient motion of granular particles especially for loose boundary channel such as alluvial channel [5].

The limited existing literatures on rigid boundary channel [6, 7] have shown that the sediment particles are eroded at lower critical values than that predicted by Shields diagram for alluvial channels. Hence, the critical values for incipient motion for rigid boundary channels are substantially lower for any particle size than for loose boundary channels [6]. Verification on existing critical velocity equations for rigid boundary channel has shown that these equations become less accurate with the predicted values lower than observed as the thickness of sediment deposits increased [8]. This could be due to the effect of 'support' from neighboring particles increased as the sediment deposits thickness increased; resulting in greater friction between particles requiring higher critical velocity and shear stress to move the particles [8].

Despite the different boundary condition in sewers/drains [9] which are of rigid boundary condition, the Shields diagram has been applied in a number of studies on sewers and drains [10, 11]. The Shields diagram was developed using a relationship based on the balance between particle weight and boundary shear stress as shown in Equation (1):

$$\theta_c = \frac{\tau_c}{gd(\rho_s - \rho)} = f\left(\frac{u_* d}{\nu}\right) = f(Re_*) \qquad (1)$$

where θ_c is the dimensionless Shields stress; τ_c is the critical shear stress [N/m^2]; g is the gravitational acceleration [m/s^2]; ρ_s is the sediment density [kg/m^3]; ρ is the fluid density [kg/m^3]; d is the grain size (normally $d = d_{50}$ for uniform sediment) [m]; $u_* = (\tau_c/\rho)^{1/2}$ is the shear velocity [m/s]; ν is the kinematic viscosity of fluid [m^2/s] and Re_* is the dimensionless grain Reynolds number. Using the data from 29 sources, a single curve representing the mean threshold values for 0.01 < Re_* < 10^5 [12] is as described in Equation (2):

$$\theta_c = \frac{0.188}{1+Re_*} + 0.0475(1 - 0.669e^{-0.015Re_*}) \qquad (2)$$

Conducting experiment for a single layer of sediment particles with size ranged from 0.6 mm to 50 mm in rectangular channels with rigid smooth bed; Novak and Nalluri [6] derived the following critical shear stress expression:

$$\frac{\tau_c}{\rho g d(S_s - 1)} = 0.065 Re_*^{-0.52} \qquad (3)$$

where S_s is the specific gravity of sediment.

By conducting experiment under "no deposit" criterion where sediment of d_{50} size ranging from 0.53 mm to 8.4 mm were fed upstream of the flume and the minimum flow with no deposition was maintained; a universal equation for smooth and rough rigid beds was developed by El-Zaemey [13] incorporating the effects of channel shape by the parameter y_0/B as follows:

$$\frac{\tau_c}{\rho g d(S_s - 1)} = 5.37(Re_*)^{-0.44}(\lambda_0)^{1.00}\left(\frac{y_0}{B}\right)^{0.51} \qquad (4)$$

where λ_0 is the bed friction factor, B is the channel bed width [m] and y_0 is the normal flow depth in the channel [13]. The bed friction factor λ_0 can be calculated using the Darcy-Weisbach's equation [7, 13]:

$$\lambda_0 = \frac{8gRS}{V^2} \qquad (5)$$

where R is the hydraulic radius; S is the channel bed slope and V is the flow velocity [m/s].

Sediment deposits in combined sewers generally has limited thickness from less than 10 mm to 60 mm [14] and up to 100 mm [15]. For rectangular open storm sewer, the sediment deposits thickness could range from 10 mm to 330 mm [16]. Thus, using existing critical values equation for rigid boundary channel in the self-cleansing design of sewer which did not incorporate the effect of sediment deposits thickness will render it inaccurate with the increasing of sediment deposits thickness. Conversely, using the Shield's threshold criterion for loose boundary channel in sewer design with limited sediment deposits thickness will produce errors.

A two-phase phenomenon involving fluid and sediment such as the study of incipient motion can be described by three components, namely i) fluid; ii) non-cohesive granular medium; and iii) flow [17]. The fluid is defined by its density ρ [kg/m^3]; the non-cohesive granular medium is defined by its density ρ_s [kg/m^3] and particle size d [m]; and the flow is defined by the hydraulic radius R [m] and gravitational acceleration g [m/s^2] [8]. The term for gravitational acceleration g can be replaced with $\gamma_s = g(\rho_s - \rho)$ where γ_s [N/m^3] is the specific weight for the sediment. By choosing d, ρ and u_* as the repeating variables, the dimensionless quantities of the two-phase phenomenon are as follows:

$$\frac{\tau_c}{\rho g d(S_s-1)}, \frac{u_* d}{\nu}, \frac{R}{d}, \frac{\rho_s}{\rho} \tag{6}$$

The term ρ_s/ρ can be excluded since the density of fluid and sediment were not varied during the experiment and would be constant. To incorporate sediment deposition thickness, the dimensionless terms of t_s/d and t_s/y_0; where t_s is the sediment bed thickness [m]; d is the sediment particle size [m] and y_0 is the normal flow depth [m] (see Figure 1) can be included in the analysis. Hence, the dimensionless terms of the incipient motion function for critical shear stress are given by:

$$\frac{\tau_c}{\rho g d(S_s-1)} = f\left(\frac{u_* d}{\nu}, \frac{R}{d}, \frac{t_s}{d}, \frac{t_s}{y_0}\right) \tag{7}$$

This paper aims to determine the effect of sediment deposits thickness on incipient motion which is still lacking in the literature. Data were obtained through incipient motion experiment in a rigid rectangular flume by varying the sediment deposits thickness. New critical shear stress equation was proposed by incorporating the effect of sediment deposits thickness in the equation.

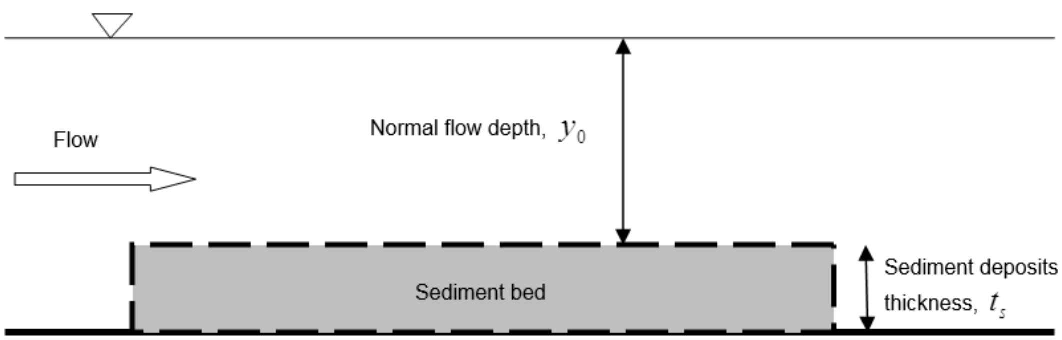


Figure 1 Depths definition for the current study

2.0 METHODOLOGY

The incipient motion experiment was conducted for six sediment deposition thickness namely; one layer $t_s = d_{50}$, 5 mm, 10 mm, 24 mm, 48 mm and 100 mm. Figure 2 shows the schematic diagram for the experimental setup while Table 1 shows the experimental parameters. The definition for incipient motion for the experiment was of general movement as defined by Kramer [18] via visual observation.

Prior to the experiment, before the pumps were turned on, the sediment deposits bed was moistened to minimize the initial filling surge. During the experiment, water level and discharge were slightly increased by controlling the pump that supplied water into the flume until incipient motion was observed. Electronic flow meter was used to determine the velocity and discharge values during the experiment. More information on the experimental procedure for the present study can be referred to Bong [19] and Bong *et al.* [8]. The observed critical shear stress was calculated using the following equation:

$$\tau_c = \rho g R S \tag{8}$$

where τ_c is the critical shear stress [N/m^2]; ρ is the density of fluid [kg/m^3]; g is the acceleration of gravity [m/s^2]; R is the hydraulic radius of flow and S is the flume slope.

Using the terms in Equation (7), multiple linear regression were performed using data from the incipient motion experiment. The best regression model from the combination of dimensionless groups in Equation (7) was selected based on four criteria: (a) coefficient of determination R^2; (b) adjusted coefficient of determination R^2_{adj}; (c) mean square error MSE; and (d) Mallow's C_p statistics. Performance test on the best new equation was done by calculating the discrepancy ratio using Equation (9). The acceptable range of discrepancy ratio is between 0.5 and 2.0 for critical shear stress determination [20].

$$Discrepancy\ ratio = \frac{\tau_{c\ predicted}}{\tau_{c\ observed}} \tag{9}$$

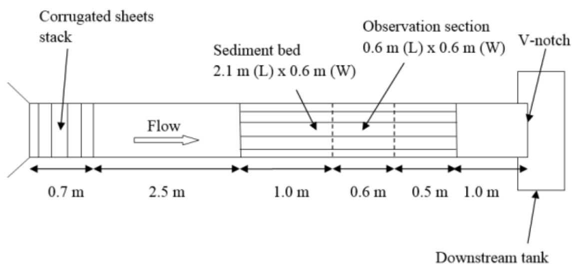


Figure 2 Schematic diagram of experimental set up (not to scale) [19]

Table 1 Range of experimental parameters for current study

Parameter	Current study
Flume width B (m)	0.6
Critical velocity V_c (m/s)	0.216 – 0.400
Normal flow depth y_0 (m)	0.02 – 0.11
Flume slope S_0	0.001 and 0.002
Sediment median size d_{50} (mm)	0.81 and 1.53
Sediment specific gravity S_s	2.54 and 2.55
Sediment bed thickness t_s (mm)	0.81 - 100

3.0 RESULTS AND DISCUSSION

3.1 Effect of Sediment Deposits Thickness

The effect of sediment deposits thickness on the critical shear stress for incipient motion can be seen by plotting θ_c against t_s/y_0 as shown in Figure 3. It was observed that θ_c increased at diminishing rate as t_s/y_0 increased for both the flume slopes used in the current study. This indicates that sediment deposits thickness have effect on the incipient motion of the sediment particles at low deposits thickness and as the thickness of deposits increases, this effect will slowly diminish. This effect could be due to the increase of friction that existed between sediment particles with the increase in sediment deposits thickness at low thickness. At thicker sediment deposits, the increase of friction between the sediment particles will slowly become negligible with further increase of the deposits thickness. From both the graphs in Figure 3; when trendlines were plotted for the data, it had been observed that the relationship between θ_c and t_s/y_0 was best fitted with a power relationship (with reasonably high R^2 value).

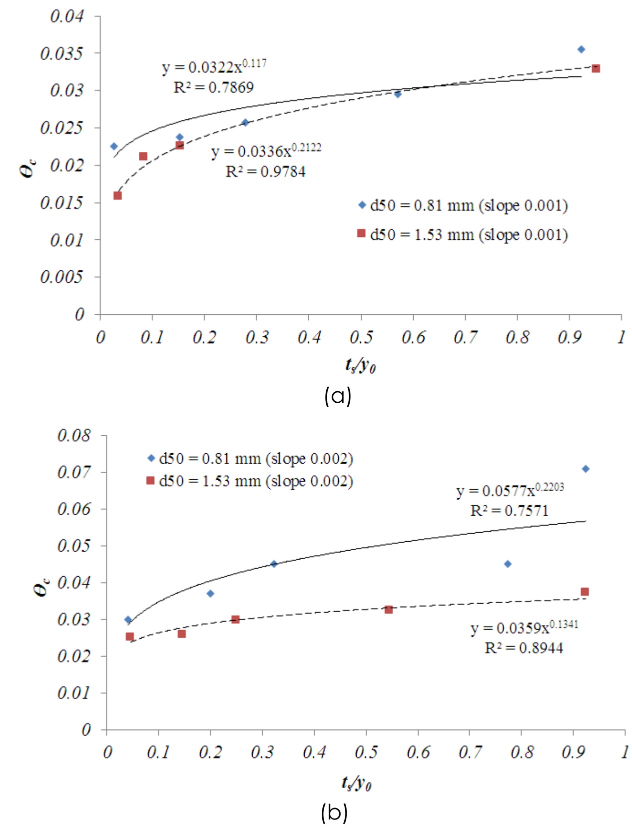


Figure 3 θ_c against t_s/y_0 for flume slope of: (a) 0.001; and (b) 0.002

Figure 4 shows the data from the current study when plotted on the Shields diagram. The single curve for the Shields diagram in Figure 4 was obtained using Equation (2) developed by Paphitis [12]. From Figure 4, θ_c values from the current study generally tend to be below the single curve for low sediment deposits thickness ($t_s = d_{50}$, 5 mm and 10 mm). As the sediment deposits thickness increased, the θ_c values from the data of the current study tend to become closer to the single curve. This confirmed the observation by Novak and Nalluri [6] where the sediment particles for rigid boundary channels (limited sediment depth) were eroded at lower shear stress than that predicted by Shields diagram for alluvial channels.

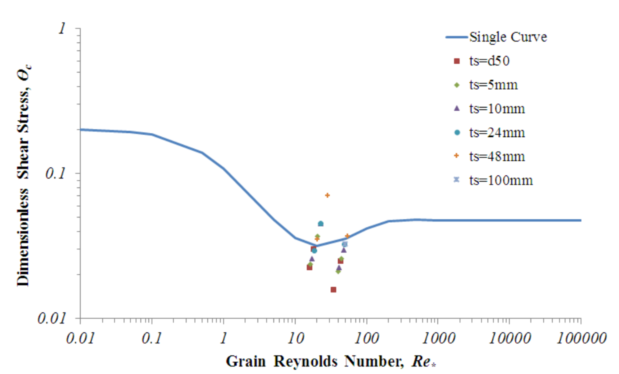


Figure 4 Data for the current study as plotted on the Shields diagram

3.2 Correlation Analysis

From both Figures 3 and 4, it was obvious that sediment deposits thickness had effect on incipient motion of rigid boundary channel. This effect can be included in the critical shear stress equation by incorporating the dimensionless terms t_s/d and t_s/y_0 as shown in Equation (7). Table 2 shows the results of Pearson correlation analysis between θ_c with t_s/d and t_s/y_0. Results from the Pearson correlation analysis showed that θ_c had considerably strong correlation with t_s/d and t_s/y_0 (having correlation value of about 0.7).

Table 2 Pearson correlation analysis for θ_c with t_s/d and t_s/y_0

Dimensionless term	θ_c
t_s/d	0.689 (*p*-value = 0.001)
t_s/y_0	0.714 (*p*-value = 0.001)

Multiple linear regressions were performed and Table 3 shows the best three models among the regression models that incorporated the dimensionless terms t_s/d and t_s/y_0 for the current study. Equation (12) was chosen for further analysis in terms of the performance test since it had both R^2 and R^2_{adj} values closest to unity among the best models in the current study as well as having the smallest MSE value with C_p value close to the number of terms in the model.

Figure 5 shows the comparison between the predicted and observed critical shear stress for the best regression model represented by Equations (10), (11) and (12). Comparing the slope for the linear best fit line; Figure 5(c) plotted with data predicted by Equation (12) had a slope value of 0.8019 which was closest to 1 (slope for the linear perfect fit line) as compared to the slope of best fit line for Equation (10) in Figure 5(a) and Equation (11) in Figure 5(b). Hence, it showed that Equation (12) was the best model to represent the data from the current study as compared to Equations (10) and (11).

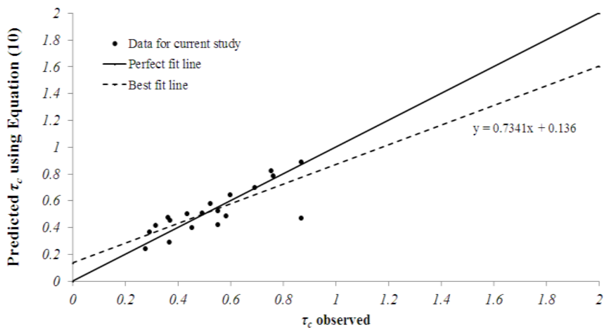
3.3 Performance Test

Performance test was done by calculating the discrepancy ratio between τ_c predicted by Equation (12) with the τ_c observed from the experiment (total of 19 data) in the current study. Discrepancy ratio values were calculated using Equation (9) and the number of values within the acceptable range of 0.5 to 2.0 was noted. Performance test were also done using existing rigid boundary equations by Novak and Nalluri [6] and El-Zaemey [13]. Figure 6(a), Figure 6(b) and Figure 6(c) show the comparison between observed and predicted critical shear stress using the data from the current study for equations by Novak and Nalluri [6], El-Zaemey [13] and Equation (12) respectively. Table 4 summarizes the results from Figure 6 for the performance test. From Table 4, it was observed that Equation (12) performed better than the existing equations by Novak and Nalluri [6] and El-Zaemey [13] by having all the predicted values within the acceptable range.

Table 5 shows the results of performance test in terms of various sediment deposits thickness. With the discrepancy ratio acceptable values range of between 0.5 and 2.0, it was observed that equation by Novak and Nalluri [6] only predicted the critical shear stress satisfactory for a single layer thickness of the sediment deposit. Equation by El-Zaemey [13] predicted satisfactory the critical shear stress values for a single layer and 5 mm sediment deposits thickness. The newly developed Equation (12) from the current study predicted the critical shear stress reasonably well for all the sediment deposits thickness used in the current study and appeared to be consistent and not much affected by the sediment deposits thickness. Hence, Equation (12) developed from the current study brought improvement in terms of the prediction power for critical shear stress values as compared to the existing equations for rigid boundary channel in the literature.

Table 3 Results for best models from multiple linear regression analysis

Model	R^2	R^2_{adj}	MSE	C_p	Eq.
$\frac{\tau_c}{\rho g d(S_s-1)} = 0.190\left(\frac{u_* d}{v}\right)^{-0.205}\left(\frac{t_s}{d}\right)^{-0.215}\left(\frac{t_s}{y_0}\right)^{0.462}$	0.57	0.48	0.011	3.99	(10)
$\frac{\tau_c}{\rho g d(S_s-1)} = 0.035\left(\frac{R}{d}\right)^{2.72}\left(\frac{t_s}{d}\right)^{-2.57}\left(\frac{t_s}{y_0}\right)^{2.79}$	0.63	0.55	0.001	4.00	(11)
$\frac{\tau_c}{\rho g d(S_s-1)} = 0.00029\left(\frac{u_* d}{v}\right)^{0.636}\left(\frac{R}{d}\right)^{8.33}\left(\frac{t_s}{d}\right)^{-7.27}\left(\frac{t_s}{y_0}\right)^{7.40}$	0.69	0.60	0.009	3.00	(12)



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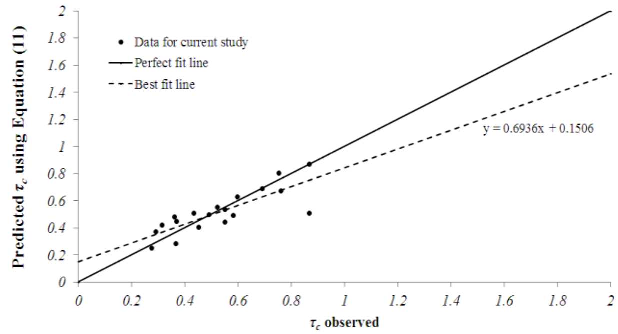

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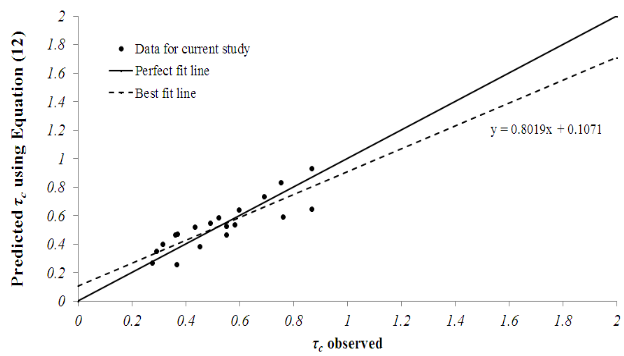

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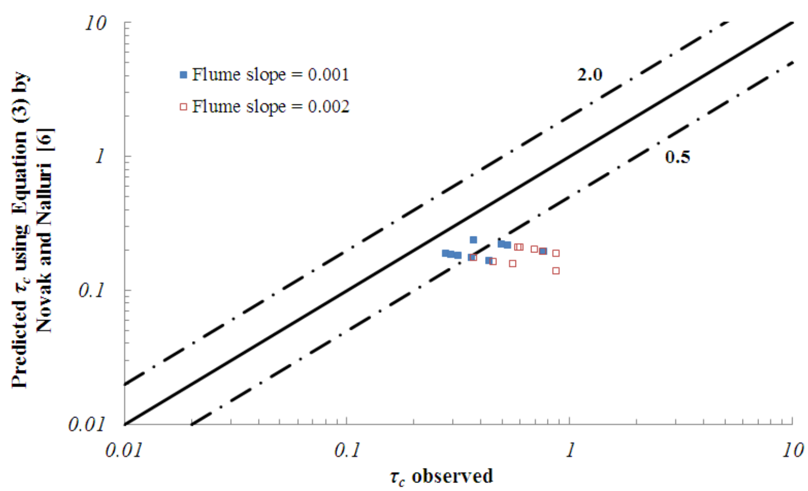
Figure 5 Comparison between observed and predicted critical shear stress by using: (a) Equation (10); (b) Equation (11); and (c) Equation (12)



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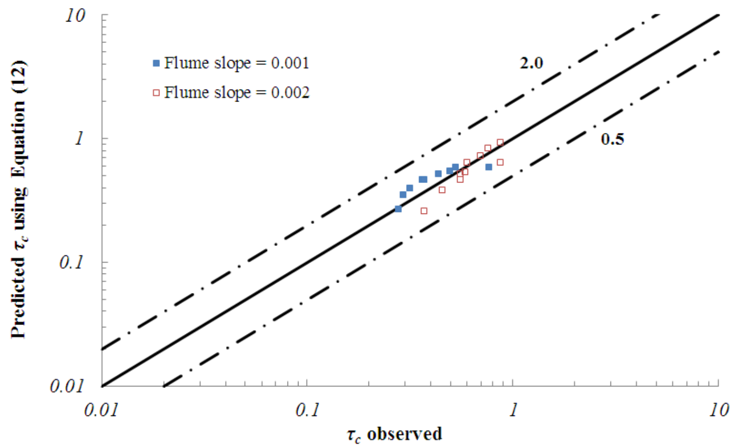

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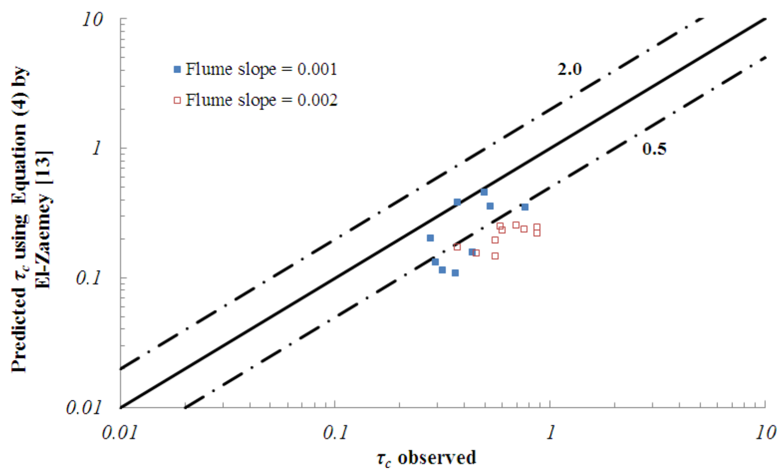


(c)

Figure 6 Comparison between observed and predicted critical shear stress for equations by (a) Novak and Nalluri [6]; (b) El-Zaemey [13]; and (c) Equation (12) from the current study

Table 4 Comparison of results from performance test according to sediment deposits thickness

Equation	Values within the acceptable discrepancy ratio (0.5 – 2.0)	
	Number of data	Percentage of data (%)
Novak and Nalluri [6]	4	21.1
El-Zaemey [13]	4	21.1
Equation (12)	19	100.0

Table 5 Comparison of results from performance test

Equation	Discrepancy ratio values for various sediment deposits thickness t_s						Average
	d_{50}	5 mm	10 mm	24 mm	48 mm	100 mm	
Novak and Nalluri [6]	0.543	0.450	0.392	0.344	0.253	0.258	0.373
El-Zaemey [13]	0.666	0.532	0.444	0.295	0.302	0.467	0.450
Equation (12)	0.971	1.058	1.071	1.115	1.001	0.772	0.998

3.4 Validation Test

To validate the newly developed Equation (12) from the current study, data from other researchers were utilized for comparison. For this purpose, data for uniform sediment from Yalin and Karahan [21] and Shvidchenko [22] were used. The existing equations in the literature, namely by Novak and Nalluri [6] and El-Zaemey [13] were also tested with the data from other researchers.

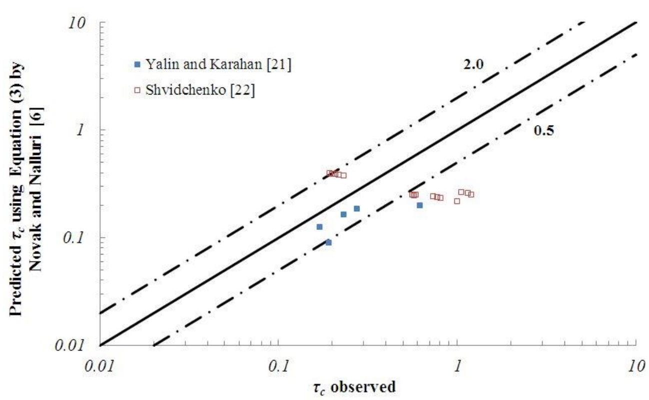
For data from Yalin and Karahan [21], five data from the experiment in turbulent flow with water as medium were selected out of a total data of 22 (16 laminar flows and six turbulent flows). The d_{50} size of the sediment used varies from 0.1 mm to 1 mm with specific gravity of 2.65. The experiment was conducted in a flume with dimensions of 21.00 m (L) x 0.76 m (W) x 0.50 m (D) with slopes of 0.003 to 0.010. The sediment thickness used in the experiment was limited and of rigid boundary. The rest of the data from Yalin and Karahan [21] was not selected due to the flow medium used was of glycerine and water mixture and not purely water while one data from the turbulent flow was using glass beads.

As for the data from Shvidchenko [22], only 15 data were chosen. The data were only chosen for the experiments with transport intensities within the two critical values of I = 10^{-4} s^{-1} and I = 10^{-2} s^{-1} as defined by Shvidchenko [22] and for uniform coarse sand (d_{50} = 1.5 mm) and fine gravel (d_{50} = 2.4 mm). The experiments for the chosen data were conducted in a flume with dimensions of 8.00 m (L) x 0.30 m (W) x 0.30 m (D) with slopes of 0.00141 to 0.0065 and the sediment deposits thickness was 5 cm (approaching loose boundary condition).

Table 6 shows the results for the validation test. From Table 6, Equation (12) developed from the current study performed better (80% of the data falls within the acceptable discrepancy ratio range) as compared to the existing equations by Novak and Nalluri [6] and El-Zaemey [13] for both sets of data from Yalin and Karahan [21] and Shvidchenko [22]. This shows that Equation (12) is able to predict the critical shear stress satisfactory for both rigid and loose boundary conditions as compared to the existing equations. Equation by Novak and Nalluri [6] seems to predict reasonably well for the critical shear stress for rigid boundary condition but performed poorly for boundary approaching loose condition. As for the equation by El-Zaemey [13], it seems to predict reasonably well the critical shear stress for thicker sediment deposits as compares to thin sediment deposits though the condition where the equation developed was for rigid boundary channel. Figure 7 shows the comparison between observed and predicted critical shear stress using equations by Novak and Nalluri [6], El-Zaemey [13] and Equation (12) respectively for the data from Yalin and Karahan [21] and Shvidchenko [22]. From the validation test, again it proves that Equation (12) developed from the current study is well suited for both rigid and loose boundary conditions as compares to the existing equations in the literature.

Table 6 Validation test for critical shear stress equations

Data source (no. of data)	Data within acceptable discrepancy ratio (0.5 – 2.0)		
	Novak and Nalluri [6]	El-Zaemey [13]	Equation (12)
Yalin and Karahan [21] (5)	3 (60%)	0 (0%)	4 (80%)
Shvidchenko [22] (15)	4 (26.7%)	9 (60%)	12 (80%)
Total (20)	7 (35%)	9 (45%)	16 (80%)



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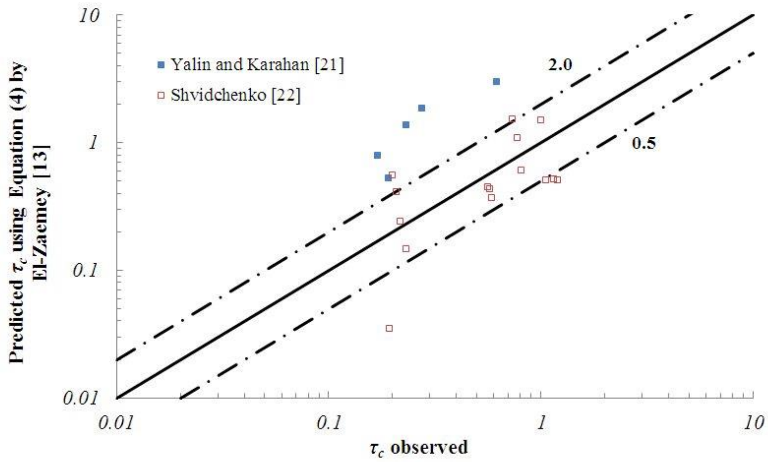

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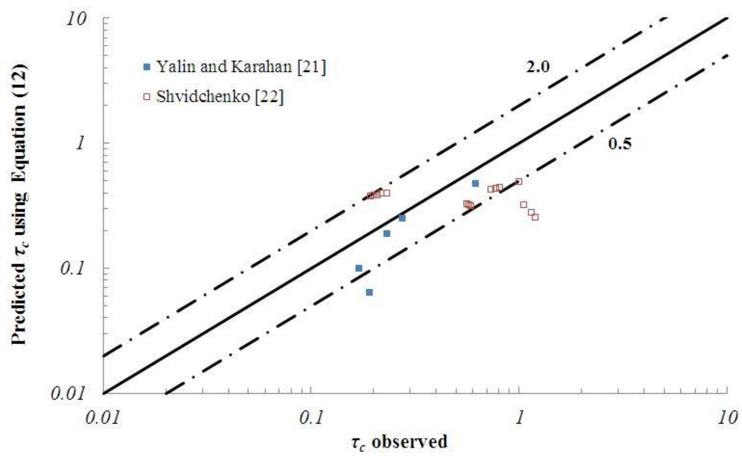

(c)

Figure 7 Comparison between observed and predicted critical shear stress using data from Yalin and Karahan [21] and Shvidchenko [22] for: (a) equation by Novak and Nalluri [6]; (b) equation by El-Zaemey [13]; and (c) Equation (12)

4.0 CONCLUSION

The current study aims to determine the effect of sediment deposits thickness on the critical shear stress for incipient motion. Findings from this study show that the sediment deposits thickness has effect on the incipient motion of the sediment particle for low sediment deposits thickness and the effect will slowly diminish as the thickness of sediment deposits increases. Existing critical shear stress equations in the literature for rigid boundary channel were proven to be inaccurate as the sediment deposits thickness increases. A new equation to predict critical shear stress was developed from the experimental data in the current study by incorporating the sediment deposits thickness. Performance and validation tests using the data from the current study and also other data from literatures show that the new equation performs better than the existing equations and brings improvement in terms of the prediction power for critical shear stress values. The new equation is an attempt towards unifying the equations for both rigid boundary and loose boundary conditions which can be use in engineering designs such as self-cleansing design of sewer system. Future experimental work can be done to determine the sediment deposits thickness to flow depth ratio where the boundary condition changes from rigid to loose.

Acknowledgement

The authors would like to thank Universiti Malaysia Sarawak for the financial support under the Small Grant Scheme (SGS) (Grant no.: F02(S149)/1129/2014(14)).

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