Bed-load Transport in Compound Rectangular Straight Channels

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Keywords: Bed-load transport; tandem and staggered vegetation; compound rectangular straight channel

Abstract. The understanding on sediment transport is important because sediment transport can affect water resource management. Therefore, the bed-load transport which is one of the main modes that sediment transport will occur is being investigated through this study. The focal aim of this study is to investigate how the presence of vegetation and the pattern of vegetation present either in tandem or in staggered arrangement affect the bed-load transport rate in compound rectangular straight channel. Laboratory experiment is conducted in order to achieve the objective of this study. The bed-load transport rate is lower in the presence of vegetation, and to compare in term of pattern of vegetation present, the bed-load transport rate is higher in tandem vegetation compare to staggered vegetation. Several bed-load transport equations are adopted in order to verify the experimental result of bed-load transport rate. However, van Rijn's equation is found to be the most suitable developed bed-load transport rate equation that can fit and validate the experiment conducted. Even though the experimental bed-load transport rate and the theoretical bed-load transport rate obtained by using van Rijn's equation is showing some difference in value, but the trend of bed-load transport rate for the various cases is still the same. Hence, it is still acceptable because previous study proven that the results obtained by using developed formula is often different from the experimental result.

Introduction

Sediment transport is a very challenging subject that has been studied for centuries by engineers and river morphologists. A lot of approaches have been developed by previous researchers regarding the sediment transport rate; the bed-load transport rate as well as the suspended load transport rate. However, results obtained from different approaches often differ significantly from each other and from observations in the field[1]**.** According toAlmedeij and Diplas,there is no particular bed-load transport rate equation that can be applied universally to all rivers and there is no existing guidelines that can be fully applied objectively or universally to facilitate the selection of an appropriate formula as the bed-load transport function [2]. Therefore, in order to compute the bed-load transport rate in this study, suitable bed-load formula must be selected wisely, in consideration of the condition of the experiment conducted, so that the experimental result can be verified. Estimation of bed-load transport rate is essential for practical computations of river morphological variations because the sediment transport through river channels has foremost effect on public safety, water resources management and environmental sustainability [3].

The study is carried out to investigate how the presence of vegetation and the pattern of vegetation present either in tandem or in staggered arrangement affect the bed-load transport rate in straight rectangular compound channel. The objectives of this study are (i) to calculate the bed-load transport rate in inbank condition and overbank condition and also in the absence and the presence of vegetation based on the data collected in the experiment conducted; (ii) to find out suitable developed bed-load transport equation that can fit the specific conditions of the experiment and validate the experimental bed-load transport rate obtained; and (iii) to further investigate several influential factors of bed-load transport rate by using the chosen developed bed-load transport equation that fit the experiment conducted.

This study focus on investigating how the presence of two-line vegetation with different arrangement on the edge of the floodplain affect bed-load transport rate in straight rectangular compound channel. In other words, there will be three cases which are the non-vegetated case, vegetation with tandem arrangement case, and vegetation with staggered arrangement case to be studied in doing the experiment for this study. The scope of this study is limited to asymmetric compound straight channel and the experiment is conducted under uniform flow with subcritical turbulent condition.

Bed-load Transport

Generally, the science of sediment transport deals with the interrelationship between flowing water and sediment particles which make it crucial to understand them in order to study the sediment transport. According to Yang, sediment particles along an alluvial bed will start to move when the flow conditions satisfy or exceed the criteria for incipient motion and the bed-load transport is said to occur if the motion of sediment particles is rolling, sliding or sometimes jumping along the bed [1]. In addition, van Rijn also state that the particles will be rolling or sliding or both in continuous contacts with the bed when the value of the bed-shear velocity just exceeds the critical value for initiation motion and as the values of the bed-shear velocity is increasing, saltation occurs [4]. Saltation is the movement of particles along the bed by more or less regular jumps. However, need to be noted is that when the value of the bed-shear velocity exceeds the fall velocity of the particles, the sediment particles can be lifted to a level at which the upward turbulent forces will be comparable with or of higher order than the submerged weight of the particles which in turn may cause the particles to go in suspension.

Factors Affecting Bed-load Transport Rate

There are several factors affecting the rate of bed-load transport. Among the factors are the flow resistance in the channel represented by the Manning's roughness coefficient (n), mean water depth in main channel (H), mean flow velocity (U), discharge (Q), boundary shear stress (τ_b), and channel bed slope (S).

The existence of vegetation on the floodplain will increase the flow resistance in the channel and decrease the flow capacity of the channel. Presence of vegetation in channel or floodplain will affect the flow resistance, sediment transport and bed forms due to scour and erosion processes. Vegetation will definitely reinforce and strengthen the soil surfaces through the growth of root systems which then produce effective soil boundary which is more resistant to soil movement and erosion [5]. Yang *et al.* also recognized that vegetation generally increases the flow resistance and affects the discharge capacity and sediment transport rate. In addition, the vegetation arrangement also plays a role in flow resistance [6]. Research by Jumain *et al*. shows that the roughness coefficient for staggered vegetation is higher than it is for tandem vegetation due to the effects of vegetation arrangement on floodplain which creates additional resistance to flow consequently contributing to higher Manning's n value [7].

On the other hand, in the presence of vegetation, to be compared with in the absence of vegetation of the same discharge, it will result in higher flow depth in the presence of vegetation. In higher flow depth, the flow velocity is lower. Lower flow velocity wills consequently lowering the boundary shear stress, thus resulting in lower sediment transport rate.

The flow velocity in compound open channel is affected by the presence of vegetation. Research by Hamidifar and Omid found that after planting the vegetation over the floodplain, the depth-average velocity over the floodplain increases whereas it increases in the main channel [8]. However, increase in the vegetation density result in decrease of the depth-average velocity in both the main channel and the floodplain. In addition, the maximum value of the streamwise velocity was also found to decrease with vegetation density. Furthermore, according to Tominaga and Nezu, the three-dimensional structures of mean velocity and turbulence are influenced by the existence of secondary currents in compound open channel [9]. The momentum transport due to the secondary currents is found to affect the primary mean-velocity field. In term of turbulence, the turbulent structures in compound open channels are characterized by large shear layers generated by the dissimilarity of velocity between main channel flow and floodplain flow [9]. In addition, Yang *et al.*stated that the presence of vegetation results in increase of the turbulence intensity. As the velocity is higher, the sediment transport rate will increase [6].

In addition, study by Ali *et al.* found that channel bed slope has a stronger effect on sediment transport capacity than unit discharge and mean flow velocity which is most likely due to increment of the tangential component of the gravity force with slope gradient [10]. The experimental results obtained by Ali *et al.* showed that in the case of non-erodible beds, the flow velocity increases steadily with slope gradient [10]. This means that as the slope is steeper, the flow velocity is higher, consequently enhance the sediment transport capacity to be higher, and hence result in higher bed-load transport rate in steeper slope.

Bed-load Transport Approach

A lot of approaches are available to calculate the rate of bed-load transport. However, not all approaches are suitable as it depends on the specific condition set for the experiment conducted.
For instance, research by Kiat *et al.* proved that the application of existing bed-load equations which are Einstein Bed Load Function, Einstein-Brown Equation, Meyer-Peter-Muller Equation and Shields Equation gave unsatisfactory performance to predict the sediment load of some local rivers in Malaysia by measuring their discrepancy ratio values [11]. Consequently, Kiat *et al.* comes up with the Modified-Einstein Equation which in turn resulted in the computed bed-load transport rates to be in much closer agreement with the actual measured values for application to the moderate-size and sand-bed streams in Malaysia [11]. Apart from that, research by Sirdari *et al.* also proved that Artificial Neural Network (ANN) and Genetic Programming (GP) models performed better than statistical (MLR)-based ones and other formulas (Equation of Meyer-Peter-Muller, Rottner, Chang, Julien, Wong and Parker, and van Rijn) in estimating the bed-load transport [12]. On the other hand, research by Ali *et al.*found that for bed load estimation, validation shows that Einstein and Meyer-Peter Muller equations have least error compared with estimation obtained from other tested equations [13].

Experimental Setup

The experiment is conducted in Hydraulic and Hydrology Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia. A straight rectangular compound channel, also known as asymmetric compound channel is the physical model used in this experiment. The channel is a 12.0m long flume which consists of 0.5m wide and 0.1m deep rectangular main channel, and a single floodplain of 0.5m wide. The bed slope of the channel is fixed at 0.001 and uniform graded sand (D_{50}=0.8mm) is used as erodible bed material and base layer with 0.2m deep for the main channel. In order to satisfy the conditions set for this study which is in the absence and the presence of vegetation, steel rods are used to simulate the vegetation. Steel rods with diameter (d) of 5mm and height of 15cm are arranged in two-line tandem and two-line staggered arrangement on the floodplain at distance between 4m to 8m from the channel inlet. Each rod displaces from each other in a distance of 2d spacing. Figures 1 and 2 show the plan view and cross section of the rectangular compound straight channel respectively. Meanwhile, Figures 3 and 4 show the two-line tandem and two-line staggered arrangement of vegetation on the floodplain respectively.

Prior to conducting the experiment, rail calibration must be carried out and uniform flow must be established in the channel. The rail calibration is important to be carried out in order to obtain accurate measurement especially the water surface and channel bed slope measurement. Then, the procedure to establish uniform flow condition can be started by switch on the pump at required discharge by adjusting the valve. Then, the tailgate is shift up until the water spill over the floodplain area and wait for a few minutes to ensure stable flow condition. After that, the tailgate is adjusted until the depth of the water flowing in the main channel is uniform. Next, water is let to flow in the channel for 24 hours.

After the 24 hours duration end, the sand trapped in the sand trap is collected and is put back into the channel at its upstream. Then, for six hours duration, every 15 minutes, the sand trapped in the sand trap is collected and weighed by using weighing scale. Each next 15 minutes is counted when the sand weighed is put back into the channel. This procedure is applied for the inbank condition and also the shallow and deep overbank condition. The inbank condition, shallow overbank condition and deep overbank condition are all of different specified discharge.

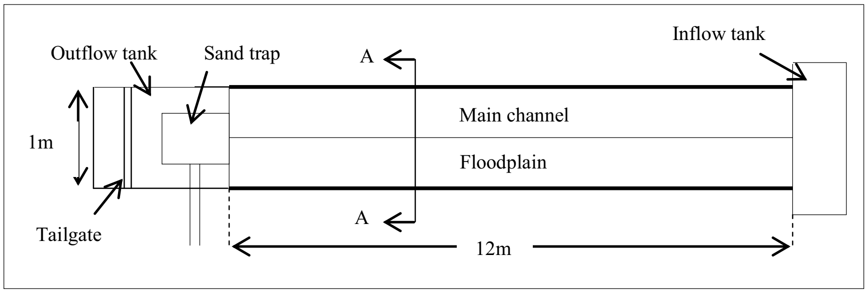

Figure 1: Plan view of rectangular compound straight channel

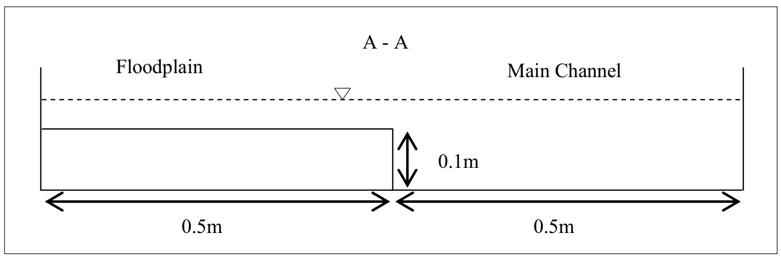

Figure 2: Cross section of the rectangular compound straight channel

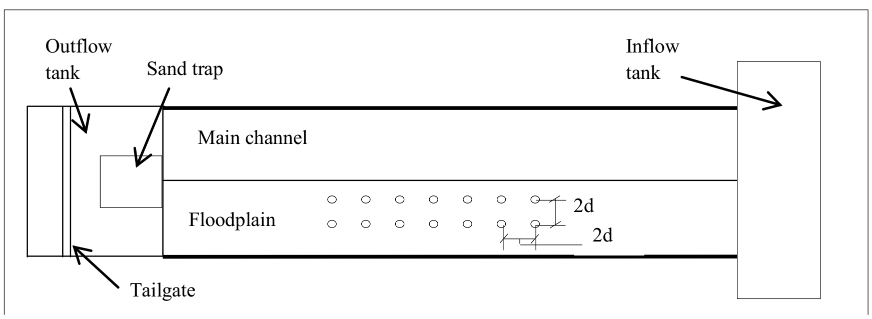

Figure 3: Two-line tandem vegetation along floodplain

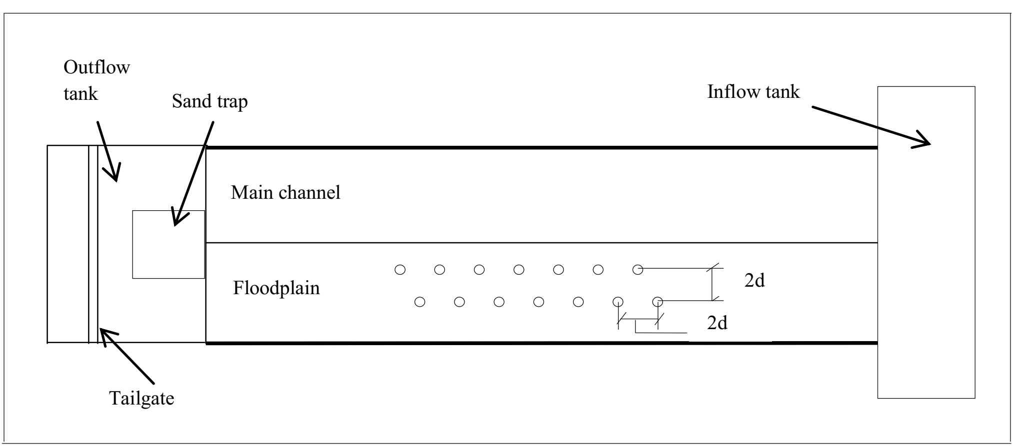

Figure 4: Two-line staggered vegetation along floodplain

Experimental Equipment

First of all, Acoustic Doppler Velocity Meter is used for velocity measurement. The velocity is measured by determining the point velocities at the section of different stage of flow for the main channel width and floodplain. The raw velocity data will then be collected using Vectrino Plus software. Then, ExploreV software is used to process raw data into processing data. Secondly, to measure the flow depth and bed profile, digital point gauge with accuracy of up to ± 0.1 mm is used. The measurement of flow depth is taken for every change of flow rates to ensure uniform flow condition. The readings are taken several times so that result of high accuracy can be obtained. Thirdly, for measurement of discharge capacity, sensor transducer of the portable flow meter is attached on the water supply pipe. The amount of discharge will then appear in the portable flow meter interface. Meanwhile, for the measurement of bed-load transport rate, the data of mass of bed-load transport need to be collected. Therefore, weighing scale is used to weight the mass of sand trapped in the sand trap. After collecting all the needed data, the experimental bed-load transport rate is calculated and the bed-load transport rate is then computed by using a few chosen developed bed-load transport equations to find the developed equation that can validate the experimental result of the bed-load transport rate.

Computation of Bed-load Transport Rate

Several developed equations of bed-load transport rate are tried which are van Rijn's equation, Meyer-Peter and Muller's equation and Shields' equation in order to choose the equation that can best fit the experiment and validate the experimental bed-load transport rate obtained through the experiment conducted. The van Rijn equation is the one that result in theoretical bed-load transport rate that is agree with the experimental bed-load transport rate. The bed-load transport rate can be computed by using van Rijn equation by following Equations (1) to (6).

a. Particle parameter, $D_* = D_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3}$ (1)

where D_{50} = particle size, s = specific density (ρ_s/ρ), ρ_s = density of sediment, ρ = density of water, g = acceleration of gravity, μ = dynamic viscosity coefficient, ν = kinematic viscosity coefficient (μ/ρ)

b. Critical bed-shear velocity, $u_{*,cr}$ according to Shields

$$\theta_{cr} = \frac{(u_{*,cr})^2}{(s-1)\,gD_{50}} \quad (2)$$

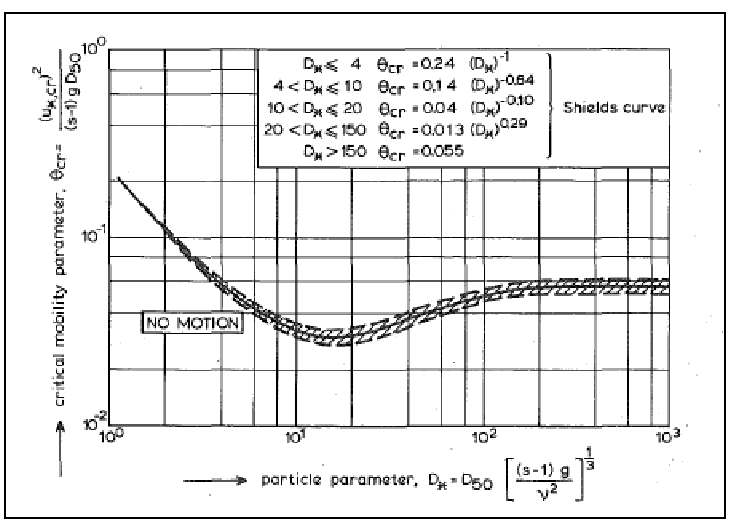

Figure 5: Initiation of motion according to Shields (Rijn, 1984)

c. Chezy-coefficient related to grains, $C' = 18\log\left(\frac{12r_b}{3D_{90}}\right)$ (3)

where D_{90} is particle size, and $r_b = r\frac{f_b}{f}$ is the hydraulic radius related to the bed according to the side-wall correction method of Vanoni-Brooks.

d. Effective bed-shear velocity, $u'_* = (g^{0.5}/C')\bar{u}$ (4)

e. Transport stage parameter, $T = \frac{(u'_*)^2-(u_{*,cr})^2}{(u_{*,cr})^2}$ (5)

f. Bed-load transport, $\frac{q_b}{[(s-1)g]^{0.5}D_{50}^{1.5}} = 0.053\frac{T^{2.1}}{D_*^{0.3}}$ (6)

Results and Discussions

Experimental Bed-load Transport Rate

Mass of bed-load transport is recorded for inbank condition and overbank condition. Inbank condition involved only non-vegetated case while overbank condition is recorded in two relative depth, which are relative depth of 0.30 and relative depth of 0.50 by which each relative depth involved non-vegetated case, tandem arrangement case and staggered arrangement case. The transported sand of 0.8mm is collected in every 15 minutes for duration of six hours and weighed using the weighing scale. Equation (7) is the bed-load transport rate equation to analyze the experimental data. The experimental bed-load transport rates for all cases are tabulated in Table 1.

$$Bed - load\ transport\ rate,\ q_b(g/s) = \frac{Mass\ of\ sediment\ transport, m\ (g)}{Duration\ of\ the\ sediment\ transport, t\ (s)} \quad (7)$$

Table 1: Experimental bed-load transport rate for all cases

Cases	Bed-load Transport Rate, q_b (g/s)		
	Inbank Condition	Overbank Condition	
		DR = 0.30	DR = 0.50
Non-Vegetated	3.755	0.088	0.029
Tandem	-	0.047	0.021
Staggered	-	0.040	0.020

Based on the tabulated data and the bed-load transport rate computed, it can be deduced that bed-load transport rate is much higher in inbank condition as compared to it is in overbank condition. This is because, in inbank condition, as the water flows only in the main channel, thus the velocity is concentrated in the main channel. Meanwhile, in overbank condition where the water will fills the entire main channel and proceeds to spill over to the floodplain areas, the velocity is no longer concentrated in the main channel. Overbank flow occurs in compound channel and according to Tominaga and Nezu, the turbulent structures in compound open channels are characterized by large shear layers generated by the difference of velocity between main channel flow and floodplain flow [9]. In this large shear-layer region, secondary currents which are associated with a pair of longitudinal vortices exist. The secondary currents which generated in the junction region between the main channel and the floodplain are driven by anisotropy and inhomogeneity of turbulence and are influencing the primary mean-velocity field. Besides, the contribution of secondary currents on momentum transport is very large near the junction [9]. Therefore, it results in lesser bed-load transported in overbank condition compared to it is in inbank condition.

In addition, it is also observed that bed-load transport rate in overbank condition with relative depth of 0.30 is higher than it is in overbank condition with relative depth of 0.50 for all three cases by which it is believed to occur due to the water depth. In order to compare the relative depth of 0.30 and relative depth of 0.50 in term of water depth in the floodplain, relative depth of 0.30 has shallow water depth in the floodplain compared to relative depth of 0.50 which has deeper water depth in the floodplain. In relative depth of 0.30 which has shallow water depth in the floodplain, the flow discharge is thus concentrated in the main channel which is in turn result in the flow velocity to be concentrated in the main channel as well. The flow velocity which concentrated in the main channel indicating high flow velocity presented in the main channel and the situation that the bed-load transport occurred only in the main channel explained the higher bed-load transport rate in relative depth of 0.30. Meanwhile, in relative depth of 0.50 which has deeper water depth in the floodplain, the flow discharge is no longer concentrated in the main channel. The flow discharge can be said uniformly distributed between the main channel and the floodplain hence the flow velocity is also uniformly distributed between the main channel and the floodplain. This mean that the flow velocity in the main channel is being reduced thus explaining lesser bed-load transport to occur in the main channel during relative depth of 0.50 as compared to it is during relative depth of 0.30. This trend of bed-load transport can be observed clearly in Figures 6 to 8 which show the comparison between the experimental bed-load transport rate during overbank condition with relative depth of 0.30 and 0.50 for non-vegetated, vegetation with tandem arrangement, and vegetation with staggered arrangement respectively.

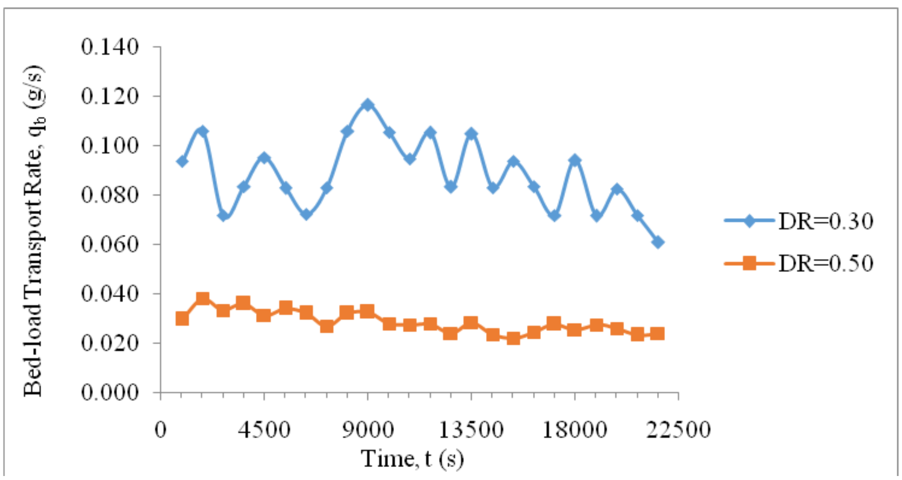

Figure 6: Experimental bed-load transport rate in overbank conditions for non-vegetated case

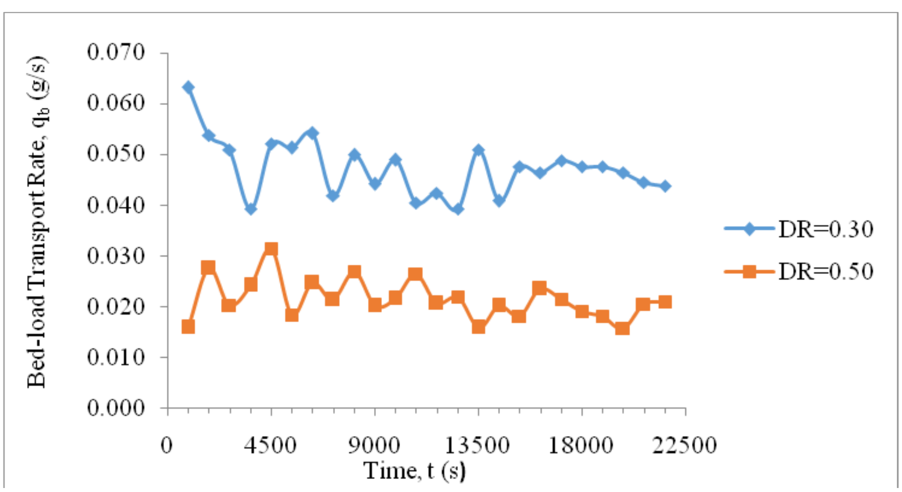

Figure 7: Experimental bed-load transport rate in overbank conditions for vegetation with tandem arrangement case

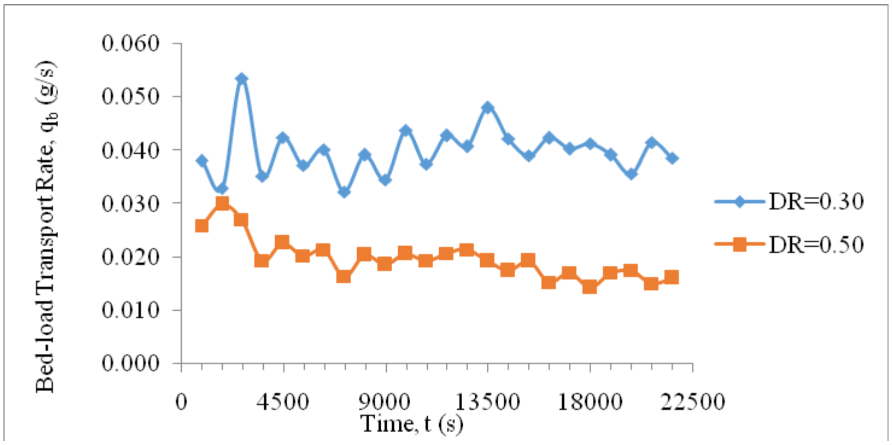

Figure 8: Experimental bed-load transport rate in overbank conditions for vegetation with staggered arrangement case

Furthermore, Figure 9 depicts a decrement of value in bed-load transport rate from non-vegetated case to tandem arrangement and then to staggered arrangement besides it is showing a trend such that the bed-load transport rate at relative depth of 0.30 is higher than it is in relative depth 0.50 as depicted in Figures 6 to 8. The bed-load transport rate in non-vegetated case is higher than in vegetated cases because the presence of vegetation on floodplain retards the water flow and caused the water depth to increase in the main channel compared to it is during the absence of vegetation on the floodplain, consequently affects the behavior of overall flow velocity [7]. Therefore, in order to maintain the flow depth in the channel for non-vegetated and vegetated cases, the flow discharge is being manipulated. Smaller flow discharge is required in vegetated cases in order to obtain the same flow depth as in vegetated case. Hence, as the flow discharge in vegetated cases is smaller than it is in non-vegetated case, which indicates smaller flow velocity in the vegetated cases, this explain the result of lesser bed-load transport in vegetated cases compared to non-vegetated case.

In addition, Jumain *et al.* also found that the presence of vegetation limits the momentum transfer between the main channel and the floodplain flows due to drag force generated by the vegetation [7]. The disruption to the flow velocity and the momentum transfer between the main channel and the floodplain flows due to the presence of vegetation on the floodplain are causing the bed-load transport rate to be lower. Meanwhile, the bed-load transport rate is higher in vegetation with tandem arrangement compared to it is in vegetation with staggered arrangement because staggered arrangement creates additional resistance to flow indicating that staggered vegetation produced larger drag force to the flow [7] hence increasing the flow resistance in vegetation with staggered arrangement case compare to vegetation with tandem arrangement case. In addition, the flow distribution for tandem arrangement is slightly better than staggered arrangement [7]. Hence, this resulted in lower bed-load transport in vegetation with staggered arrangement compared to it is in vegetation with tandem arrangement.

However, it can be observed that the difference in bed-load transport rate between the non-vegetated case, vegetation with tandem arrangement case, and vegetation with staggered arrangement case is not that significant. The discrepancy ratio between the non-vegetated case and vegetation case with tandem arrangement for relative depth 0.30 and 0.50 are 46.6% and 27.6% respectively. Meanwhile, the discrepancy ratio between the non-vegetated case and vegetation case with staggered arrangement for relative depth 0.30 and 0.50 are 54.5% and 31.0% respectively. The small discrepancy of bed-load transport rate between these cases is believed to happen because the study concentrates only on two-line vegetation which placed on the floodplain at distance between 4m to 8m from the channel inlet. This limitation caused the effect of presence of vegetation and the effect of arrangement of vegetation present on the floodplain towards the bed-load transport rate to be mild. The higher impact of the presence of vegetation with different arrangement towards the bed-load transport rate probably can be seen if more vegetation is placed on the floodplain.

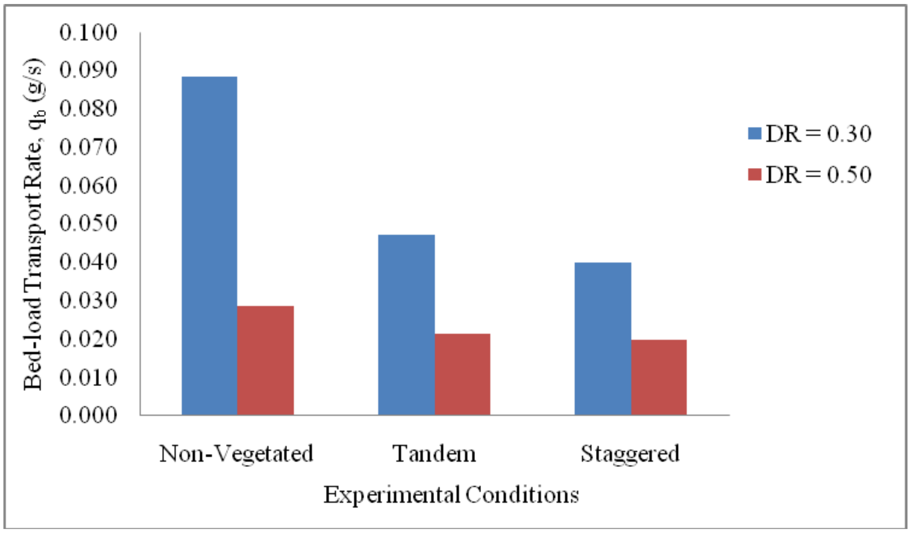

Figure 9: Experimental bed-load transport rate in overbank conditions of different cases

Theoretical Bed-load Transport Rate

A lot of equations have been developed by many researchers to compute the bed-load transport rate. However, it is totally noted that certain equation can only fit certain experiment as each experiment is unique by its own specific conditions. Yang also stated that results obtained from different approaches often differ significantly from each other and from observations in the field [1]. Therefore, in the process of validating the experimental result of bed-load transport rate of this study, a few equations have been tried out such as van Rijn, Meyer-Peter and Muller (MPM), and Shields.

Shields' equation is found to display an increment of value in bed-load transport rate from non-vegetated case to tandem arrangement and then to staggered arrangement which is in opposite to the trend of experimental bed-load transport rate. Hence, Shields' equation cannot be used to validate the experimental bed-load transport rate of this study. Meanwhile, by using Meyer-Peter and Muller (MPM) equation, bed-load transport rate cannot be computed. This is because it is found that the critical velocity, U_{cr} for this experiment is 0.38 m/s which mean that there is no bed-load transport recorded below this value. Since the velocity used in this experiment is smaller than the U_{cr}, therefore MPM equation is not suitable to be used to validate the experimental bed-load transport rate of this study. On the other hand, among all three equations, van Rijn equation is the only equation that found to agree with the experimental bed-load transport rate hence validating the experimental result to be true. Table 2 and Figure 10 show the bed-load transport rate obtained by using the van Rijn equation. After the theoretical result of bed-load transport rate is obtained by using van Rijn equation, the experimental result is compared with the theoretical result as displays in Figures 11 and 12 for overbank condition with relative depth of 0.3 and 0.5 respectively.

Based on Figures 11 and 12, it can be observed that the value of experimental bed-load transport rate is of quite a significant difference compare to the theoretical bed-load transport obtained by using van Rijn equation. This is believed to happen due to the systematic errors which are associated with a flaw in the equipment or in the design of the experiment. For example, the uses of obsolete equipment in conducting the experiment will absolutely affecting the accuracy of the experimental result obtained. In addition, due to imperfect condition during the construction of the physical model, the roughness surface between main channel wall and floodplain may occur hence increasing the flow resistance along the channel which in turn causing the bed-load transport rate to be lower than it should be. Therefore, the experimental bed-load transport rate is observed to be much lower than the theoretical bed-load transport rate. However, it is to be noted that the trend of bed-load transport is the same for both the experimental and theoretical result which is the bed-load transport rate is higher in relative depth of 0.3 compare to it is in relative depth of 0.5 and the bed-load transport rate is decreasing from the non-vegetated case to vegetation with tandem arrangement case, and then to vegetation with staggered arrangement case. In addition, study by Ali *et al.* which also result in such that the bed-load transport rate measured is higher than the bed-load transport rate computed by using van Rijn equation is indicating that the result obtained through the analysis by using van Rijn equation is correct [13].

Table 2: Bed-load transport rate in overbank conditions using van Rijn equation

Cases	Bed-load Transport, q_b (g/s)	
	DR = 0.30	DR = 0.50
Non-Vegetated	0.0174	0.0164
Tandem	0.0168	0.0050
Staggered	0.0087	0.0003

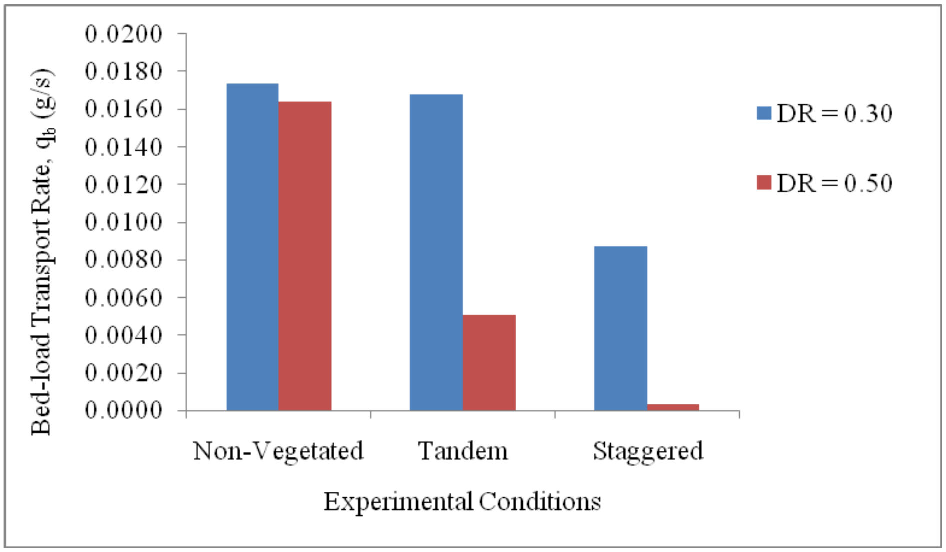

Figure 10: Bed-load transport rate in overbank conditions using van Rijn equation

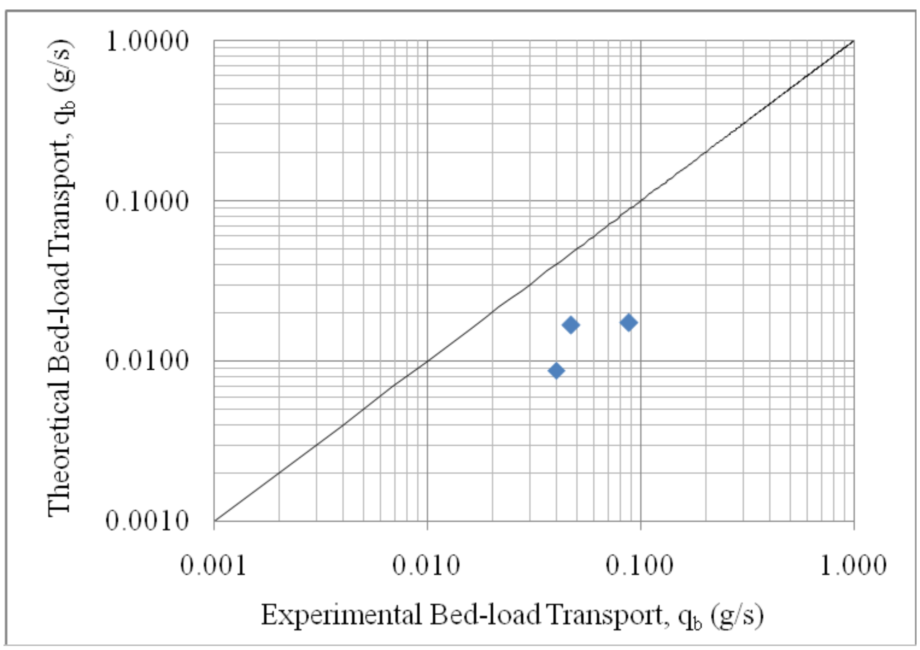

Figure 11: Theoretical bed-load transport (using van Rijn equation) against experimental bed-load transport in overbank condition of DR = 0.30

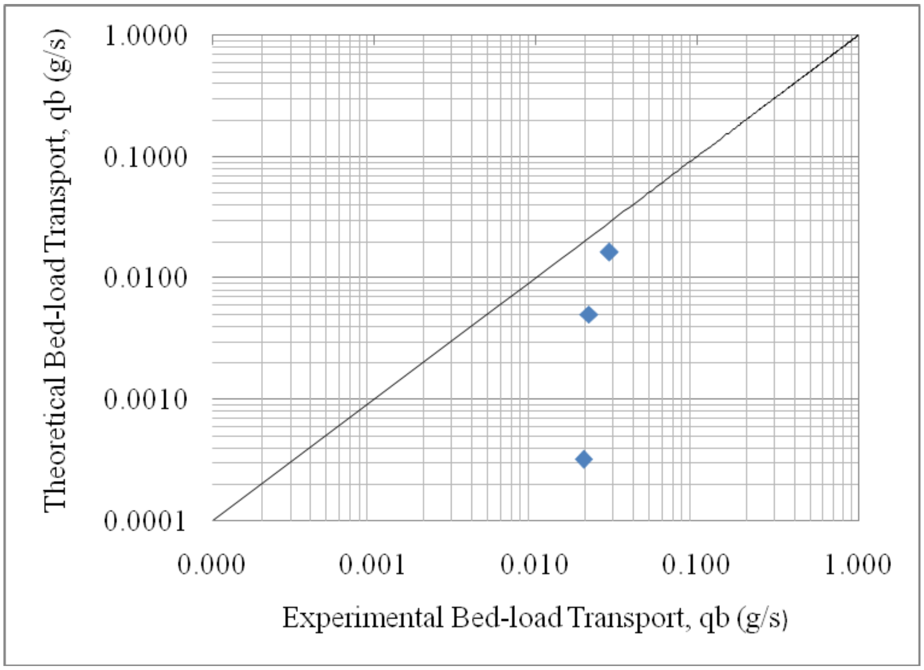

Figure 12: Theoretical bed-load transport (using van Rijn equation) against experimental bed-load transport in overbank condition of DR = 0.50

Influential Factors of Bed-load Transport Rate

There are several factors that significantly affecting the bed-load transport rate such as the channel bed slope (S), flow velocity (U) and sediment size (D_{50}). van Rijn equation which is found to agree with the experimental result of the bed-load transport rate of this study is used to analyze the effect of channel bed slope (S), flow velocity (U) and sediment size (D_{50}) towards the bed-load transport rate. The effect of channel bed slope on the bed-load transport rate is however cannot be analyzed by using van Rijn equation because as the channel bed slope is manipulated, some other parameters used by van Rijn equation in computing the bed-load transport rate need to be manipulated as well. The affected parameters if the channel bed slope is manipulated are the flow velocity and the flow depths which are absolutely cannot be simply estimate in order to obtain correct analysis.

However, study by Ali *et al.* has proven the effect of bed slope on bed-load transport rate [10]. The experiment conducted by Ali *et al*. results in the slope gradient to be the one that has a stronger impact on transport capacity than unit discharge and mean flow velocity due to the fact that the tangential component of gravity force increases with slope gradient [10]. For the experiment, Ali *et al.* adjusted the flume bed to four slope gradients which are 5.2%, 8.7%, 13.2%, and 17.6% in order to analyse the impact of slope gradient on sediment transport capacity [10]. The experimental results showed that in the case of non-erodible beds, the flow velocity increases steadily with slope gradient [10]. This means that as the slope is steeper, the flow velocity is higher, consequently enhance the sediment transport capacity to be higher, and hence result in higher bed-load transport rate in steeper slope.

Meanwhile, Tables 3 and 4 show the effect of flow velocity (U) and sediment size (D_{50}) towards the bed-load transport rate, respectively. By referring to Table 3, it shows that as the velocity is higher, the bed-load transport rate is higher. This is because, when the velocity is high, it triggers the sediment particle to move even more and thus increasing the bed-load transport rate. On the other hand, Table 4 is showing that the bed-load transport rate is higher when smaller sediment size is used. The sand used in this experiment is 0.8mm which is classified as non-cohesive coarse sand. According to Hassanzadeh, the non-cohesive soils is generally consist of larger discrete particles than cohesive soils and the movement of these particles depends on the physical properties of the individual particles such as size, shape and density such that the particle size is the most important physical property of the sediment particle [14]. This is because particle size has a direct effect on the mobility of the particle. As the sediment particle size is smaller, it requires lower threshold of force for initiation of motion or in other word smaller sediment particle size require less force for it to be transported. Thus, when smaller sediment particle size is compare to larger sediment particle size while maintaining the same velocity for both, it can be observed that the bed-load transport rate of the smaller sediment particle size is higher than it is for the larger sediment particle size.

Table 3: Bed-load transport rate at different flow velocity

Relative Depth	Bed-load Transport Rate, q_b (g/s)	
Cases	U = 0.29 m/s	U = 0.50 m/s
DR = 0.30		
Non-Vegetated	0.0174	0.0255
Tandem	0.0168	0.0246
Staggered	0.0087	0.0139
DR = 0.50		
Non-Vegetated	0.0164	0.0204
Tandem	0.0050	0.0069
Staggered	0.0003	0.0008

Table 4: Bed-load transport rate at different sediment size

Relative Depth	Bed-load Transport Rate, q_b (g/s)	
Cases	D50 = 0.8mm	D50 = 0.6mm
DR = 0.30		
Non-Vegetated	0.0174	0.0258
Tandem	0.0168	0.0251
Staggered	0.0087	0.0151
DR = 0.50		
Non-Vegetated	0.0164	0.0234
Tandem	0.0050	0.0092
Staggered	0.0003	0.0019

Conclusion

Generally the experiment conducted aims to study the bed-load transport in straight rectangular compound channel and specifically to investigate the effect of presence of vegetation on floodplain towards the bed-load transport rate. In order to validate the experimental bed-load transport rate, several developed bed-load equations are tried out to choose the one that can validate the experimental bed-load transport rate. Apart from that, other influential factors of bed-load transport are further investigated by using the developed bed-load equation that agrees with the experimental bed-load transport rate. The followings are the findings of the experiment conducted and the findings from the analysis that have been carried out.

The bed-load transport rate is higher in inbank condition compare to it is in overbank condition. This is because, in overbank condition, there are large shear layers generated by the difference of velocity between main channel flow and floodplain flow. In this large shear-layer region, secondary currents which are associated with a pair of longitudinal vortices exist and it is influencing the primary mean-velocity field causing the bed-load transport rate to be lower in overbank condition. Meanwhile, the bed-load transport rate is higher in overbank condition with relative depth of 0.30 compared to it is in overbank condition with relative depth of 0.50. This is because relative depth of 0.50 has higher flow depth, thus lower flow velocity compare to relative depth of 0.30. The bed-load transport rate is lower in the presence of vegetation because the presence of vegetation disrupts the flow velocity and the momentum transfer between the main channel and the floodplain flows. In addition, the bed-load transport rate is higher in tandem vegetation compare to staggered vegetation because the staggered arrangement creates additional resistance to flow.

Among the three developed bed-load equations that have been tried which are van Rijn, Meyer-Peter and Muller, and Shields' equations, van Rijn equation is the equation that produce theoretical bed-load transport rate that agree with the experimental bed-load transport rate. Shields' equation is found to display an increment of value in bed-load transport rate from non-vegetated case to tandem vegetation and then to staggered vegetation which is in opposite to the trend of experimental bed-load transport rate. Meanwhile, by using Meyer-Peter and Muller (MPM) equation, bed-load transport rate cannot be computed. This is because it is found that the critical velocity, U_{cr} for this experiment is 0.38 m/s which mean that there is no bed-load transport recorded below this value. Since the velocity used in this experiment is smaller than the U_{cr}, therefore MPM equation is not suitable to be used to validate the experimental bed-load transport rate of this study.

Flow velocity, sediment size and channel bed slope did influence the bed-load transport rate. As the velocity is higher, the bed-load transport rate is higher. Meanwhile, bed-load transport rate is higher when smaller sediment size is used. In addition, steeper bed slope result in higher bed-load transport rate.

Recommendations

There are a few recommendations for future research regarding this experiment of investigating the bed-load transport rate in straight rectangular compound channel in the case of absence and presence of vegetation. The recommendations that can be applied to enhance the experimental result and to have comprehensive understanding regarding the bed-load transport rate are as follows:

a) Use steeper bed-slope, smaller sediment size, and higher discharge value to have higher flow velocity so that the bed-load transport is more significant.
b) Vary the cases by varying the spacing between the rods to investigate the effect of vegetation density towards the bed-load transport rate.
c) Place the rod along the floodplain and not only on certain part on the floodplain so that the experimental bed-load transport rate is accurate.
d) Use another developed bed-load transport equation that involve bed-shear stress and drag force parameters to investigate how these parameters affect the bed-load transport rate and ensure that the equation can validate the experimental bed-load transport rate.
e) Use another method instead of bed-load equation in estimating the bed-load transport such as Artificial Neural Network (ANN) and Genetic Programming (GP) models.

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