Effect of Submerged Artificial Vegetation on Flow and Trapping Sediment

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Abstract. This study is about the effect of flow and trapping sediment using submerged artificial vegetation. The purpose of this study is to analyse the velocity of vegetation layer and upper layer, global flow resistance and determine the relationship between Total Suspended Solid (TSS) with flow velocity and vegetation density. Rigid cylinder model with diameter of 8 mm was used to simulate the artificial vegetation. The flow velocity on vegetation layer is found to be lowered compare to upper layer which result S-curve of vertical velocity profile. Besides, comparison of estimated and measured data of flow velocity and global flow resistance with previous researcher in term of Root Mean Square Error (RMSE) also provided in this study. It is shown that at the lowest flow velocity, more sediment was trapped at the channel bed, where the TSS were increased from slow, moderate to fast velocity. The increment percentage of TSS value from slow to fast velocity were within 13.04% to 36.11% for vegetation density (m) of 1056 m⁻². Next, for m of 1533 m⁻², the increment percentage of TSS value from slow to fast velocity were within 5.55% to 5.26%. while m for 2756 m⁻², the increment percentage of TSS value from slow to fast velocity were 6.67% and 6.25%. Slower flow velocity and higher vegetation density give the best performance in trapping sediment. It proves that the flow velocity and vegetation density play the key role for trapping sediment.

1. Introduction
Rivers need more space in order to support the increase of water level because of the climate change conditions. The awareness creates recent river management to permit natural process of erosion and sedimentation. “Suspended Solids (SS) from improper earthworks and land clearing activities were the main contributors to river pollution” [1]. The water quality status of rivers was classified based on the Interim National Water Quality Standard (INWQS) for Malaysia. Suspended solid is one of the parameters that have been taken to classify the water quality. Improper slope management and soil erosion at construction areas become a major threat, as a rapid development of construction in Malaysia. Many construction sites provide silt trap or sediment trap, but not totally effective. Silt, fine sand, clay and small particles still can trespass and enter to main channel or river. Worst, certain developer didn’t provide any sediment trap due to space or budget issues. In order to overcome this issue, buffer zone must be provided before sediment enters to the main channel. Vegetation in the buffer zone will lengthen the time flow and increase the resistance that acts as filter to the nature.

Rigid cylinder recently used in the experiment to analyse the relationship of vegetated to control floodplain. Several researches have been carried out to study the effect of vegetation on overflow, shear-stress, hydraulic conveyance, erosion, and turbulent coherent and flow alteration. It can be accepted to
be used the rigid cylinder because of the identical stems is uniformly distributed. [2] conclude that the swaying of the vegetation will leads to non-uniform profile of vegetation properties over height. In addition, the experimental study has shown that complicated vegetation structure, such as those leaves, lead to complicated effects on the break-up of turbulent vortices. Thus, to a more complex description of the vegetation. The statement also supports by [3] which state that the presence of submerged rigid cylinder will result in simple expression is available that describe the average flow velocity. Previous research by [4] prove that the rigid cylinder can have friction coefficient and element Reynolds number similar for real and artificial plants when larger diameter, $d$ is use ($>8$ mm). Vargas-Luna et al. [4] shows that the use of rigid cylinder neglects the characteristic of foliage of plant under flowing water that result decrease of projected area and drag forces. A few study [3, 13] also had been conducted to investigate the arrangement of cylinders influence vertical velocity profile, turbulent structure, bed load, and suspended load.

Vegetation influence vertical velocity profile. Thus accurate description is important in order to understand the interaction of the flow. Hu et al., [6] and Vargas-Luna et al.[7] made the comparative and validation of prediction model in term of velocity profile. The flexibility, density of the vegetation and degree of submergence play important role to the effect of vertical velocity by the relation between water depth and vegetation height [8-9]. Local sediment transport decreases substantially in the presence of vegetation [10-11]. The decrease is related with the reduction of flow velocity and shear stress at the bed due to increase of hydraulic resistance [12]. Based on Yang & Choi [13], velocity in the vegetation is assume as constant and velocity for the upper layer is logarithmic which is consider two-layer approach with submerged vegetation in depth limited open channel. The analysis is performed by using Chezy’s coefficient (resistance predictor) and was compared with measured data.

For global flow resistance, Vargas-Luna et al., [7] made the conclusion where, the model of Kloppstra [14], Van Velzen et al. [4] and Baptist [2] have performed same behavior for both rigid and flexible vegetation. The method proposed by Yang & Choi [13] provide better result for flexible vegetation, whereas model by Cheng [3] give better result for rigid case. Others model by Huthoff & Augustijn [3] and Stone and Shen [15] give lowest performance. The objective of this research is to investigate the relationship between flow and sediment transport in depth-limited flow with submerged vegetation at different vegetation density.

2. Research Methodology

This study concentrates on the influence of flow velocity and vegetation density on trapping sediment. The experiment had been conducted in 2 m long, 0.3 m wide and 0.35 m height of open channel flume. The flume set-up as in Figure 1 with 2% slope. The rigid cylinder stick with diameter, $d$ of 8 mm was used to indicate as submerged vegetation in an open channel. The rigid cylinder stick was installed in staggered arrangement with a vegetation density ($m$) of 1056, 1533 and 2756 stems per m$^2$. Sand with size of 0.3 mm and height of 0.02 m was laid evenly between the rigid cylinder stick on the precast channel bed. The inflow is slowly setup to avoid movement of the sand bed until it reaches 0.2 m water depth. Next, the speed of the inflow was adjusted. The sand of 500 g with size of 0.15 mm was injected at the distance of 0.1 m before it reaches the vegetation zone. Figure 1 shows the model setup.

![Figure 1](image_url)
2.1. Bed sediment
In order to determine the particle size distribution of the sediment bed material, sieve analysis was carried out. Samples of the sand bed were sieve according to BS1377: Part 2 (1990) with sieve ranges from 0.063 mm to 10 mm. Next, the samples were weighted and oven dried for 24 hours before sieving using a mechanical shaker with sieve range accordance with BS 1377: Part 2 (1990). After 20 minutes, the weight of sand retained in each sieve was weighted and the size were calculated. Figure 2 shows the mechanical shaker and Figure 3 shows the particle size distribution presented in a semi-logarithmic plot.

![Figure 2. Mechanical shaker machine](image1.png)

![Figure 3. Semi-logarithmic plot](image2.png)

2.2. Rigid Cylinder Model
The rigid cylinder was used as an artificial vegetation in this study. The diameter of the stick is 8 mm and 0.12 m length. The selection of this model is made after take into account the complicated vegetation structure such as those leaves, swaying and turbulent effect. The arrangement of rigid cylinder is in staggered with spacing, $s$ = 0.023 m. The vegetation zone with length of 0.3 m and wide of 0.15 m wide was made up from concrete with thickness of 0.02 m. The rigid cylinder is embedded on the concrete permanently to avoid any movement during the test. Figure 4 shows the rigid cylinder model setup.

![Figure 4. Rigid cylinder model setup](image3.png)

2.3. Velocity and discharge measurement
The rectangular flume was filled with 0.2 m of water. The flow was adjusted into three mode which were slow, moderate and fast by setting the rotation of the tap accordingly. The grid with dimension of 0.05 m x 0.05 m was setup on the wall of the rectangular flume as an indicator for distance and height to measure the velocity of the flow with the length of 0.3 m and height of 0.15 m as shown in the Figure 5. The ink was injected according to the depth, $z$. For vegetation layer, the depth, $z$ is 0.05 m, middle layer depth, $z$ is 0.10 m and upper layer depth, $z$ is 0.15 as shown in the Figure 6. The time taken of the ink passed each grid line were recorded. The experiment was repeated with different vegetation density. All data were analysed and recorded. The formula of the velocity is calculated as in equation (1)

$$v = \frac{\text{distance (m)}}{\text{time (s)}} \quad (1)$$
2.4. Global flow resistance and Total Suspended Solid (TSS) measurement

Global flow resistance (resistance predictor) is measured by using Chezy’s equation.

\[ \bar{u} = C_r \sqrt{h i_b} \]  \hspace{1cm} (2)

where, \( h \) is water depth, \( C_r \) is global flow resistance coefficient, \( i_b \) is slope of the channel.

After 2 minutes, the sand was injected. The 500 ml of water sample was collected before and after the vegetation zone. Total of 18 samples were collected. Suspended solid is a material that will retain on filter paper when sample is filtered. The filter paper will be dried at 100°C for 1 hour and cooled in desiccator. Total suspended solid is measured by weighing the retain solid from filter paper. The process Total Suspended Solid (TSS) have shown in Figure 7. The Total Suspended Solid (TSS) were calculated by using equation (3).

\[ \text{Total Suspended Solid, mg/L} = \frac{(A-B) \times 1000}{C} \]  \hspace{1cm} (3)

where,

- \( A \) = weight of filter and aluminium tray + residue in mg.
- \( B \) = weight of filter and aluminium tray in mg.
- \( C \) = volume of sample filtered in mL.
3. Results and Discussions

3.1. Vertical velocity profile

The test is conducted with three different density and velocity. The vegetation zone with dimension of 0.3 m width and 0.3 m length is marked with three different depth, \( z \). The vertical velocity profile was analyzed at three vegetation density, \( m = 1056 \ m^{-2}, 1533 \ m^{-2} \) and 2756 \( m^{-2} \), as shown in Figure 8, 9 and 10. The flow velocity at vegetation layer is found to be slower compared to upper layer for all density. The flow velocity on vegetation layer is found to be lower compared to upper layer which results in an S-curve of vertical velocity profile. Besides, most results shown higher flow velocity at the starting and ending of vegetation zones. This is due to the vegetation resistance along the vegetation zone.

![Figure 8. Vertical Velocity Profile for velocity at density, \( m = 1056 \ m^{-2} \)](image1)

![Figure 9. Vertical Velocity Profile for velocity at density, \( m = 1533 \ m^{-2} \)](image2)

![Figure 10. Vertical Velocity Profile for velocity at density, \( m = 2756 \ m^{-2} \)](image3)

3.2. Analysis of velocity at vegetation and upper layer of the submerged vegetation

Velocity of vegetation layer and upper layer was analyzed by plotting the estimated against measured values. Based on the Figure 11, for vegetation density, \( m = 1056 \ m^{-2} \), result from Klopstra [14] shown that the vegetation layer and upper layer are overestimated for all types of velocity. Next, result shown by Yang and Choi [13] performed well for fast velocity at both vegetation and upper layer. Cheng [3] present good agreement at moderate velocity in vegetation layer. The upper layer is found to be overestimated for all types of velocity. Thus, it can be concluded that, for equation provide by Cheng [3] gives better performance with the lowest RMSE of 0.039 at vegetation layer for moderate velocity. Whereas, Yang and Choi [13] gives better performance at upper layer with the lowest RMSE of 0.157.

Next, for a vegetation density, \( m = 1533 \ m^{-2} \), result shown by Klopstra [14] were overestimated for all types of velocity at vegetation layer and significant different for upper layer. Yang and Choi [13] reported better performance for moderate and fast velocity at vegetation layer but weak performance for all type of velocity at upper layer. Lastly, Cheng [3] gives the best accuracy for slow and moderate velocity at vegetation layer but show an overestimated data for all types of velocity at upper layer. Thus,
Yang and Choi [13] equation is found to be most suitable to be used with lowest RMSE of 0.045 and 0.124 at vegetation and upper layer respectively.

Meanwhile, for vegetation density, \( m = 2756 \text{ m}^{-2} \), Klopstra [14] still show its significant different with highest overestimated data for all types of velocity at upper layer. But different with result from Yang and Choi [13] where its present over measured data for both vegetation and upper layer. Cheng [3] show better performance for fast velocity at upper layer but weak in vegetation layer for all types of velocity as shown in Table 1. Thus, Yang and Choi [13] show the best performance for both vegetation and upper layer with lowest RMSE of 0.142 and 0.087 respectively.

![Figure 11. Submerged artificial vegetation; measured against estimated flow velocity for Klopstra et al. [14], Yang and Choi [13] and Cheng [3].](image)

### Table 1. Root mean Square Error (RMSE) for velocity at vegetation and upper layer of submerged vegetation

| Models                  | Vegetation density = 1056 m\(^{-2}\) | Vegetation density = 1533 m\(^{-2}\) | Vegetation density = 2756 m\(^{-2}\) |
|-------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
|                         | Vegetation layer | Upper layer | Vegetation layer | Upper layer | Vegetation layer | Upper layer |
| Klopstra (1997)          | 0.171             | 0.638       | 0.171             | 0.899       | 0.081             | 1.696       |
| Yang and Choi [13]       | 0.065             | 0.157       | 0.045             | 0.124       | 0.142             | 0.087       |
| Cheng [3]                | 0.039             | 0.325       | 0.051             | 0.313       | 0.192             | 0.128       |

3.3. **Analysis of global flow resistance**

The global flow resistance is computed in term of Chezy’s coefficient and the graph of estimated against measured was plotted. The equation of Cheng [3] exhibits the lowest performance when its shows overestimate of global flow resistance for a vegetation density, \( m = 1056 \text{ m}^{-2} \) as shown in Figure 12 with RMSE is equal to 5.955. Others model present overestimate global flow resistance as well. However, Stone and Shen [15] equation gives better estimation for fast velocity with lowest RMSE of 3.067. Slow velocity is not practicable to be use in the equation because it’s given significant different compare to moderate and fast velocity.

Next, for a vegetation density, \( m = 1553 \text{ m}^{-2} \), Cheng [3] still exhibit lowest performance with highest RMSE of 5.206. Yang and Choi [13] and Huthoff & Augustijn [3] (2007), show almost equal estimated
value with RMSE of 2.739 and 2.8 respectively. Equation performed by Stone & Shen [15] provide better result when perform at fast velocity and show lowest RMSE of 1.732.

Lastly, for a vegetation density, \( m = 2756 \, m^{-2} \), all result exhibit over measured data. Stone & Shen [15] show lowest performance compare to other researchers with highest RMSE stated which is 6.052. Cheng [3] exhibit better performance compare to previous density with lowest RMSE of 1.051. Table 2 show the value of RMSE relative to the method considered, showing the degree of accuracy.

![Graphs showing estimated vs measured flow resistance for different vegetation densities](image)

**Figure 12.** Submerged artificial vegetation; measured against estimated global flow resistance for Stone and Shen [15], Huthoff & Augustijn [3], Yang and Choi [13] and Cheng [3]

| Vegetation density | RMSE  |
|--------------------|-------|
| \( 1056 \, m^{-2} \) | 3.067 | 1.732 | 6.052 |
| \( 1533 \, m^{-2} \) | 3.642 | 2.800 | 3.283 |
| \( 2756 \, m^{-2} \) | 5.955 | 5.206 | 1.051 |

**Table 2.** Root Mean Square Error for global flow resistance

### 3.4. Total Suspended Solid (TSS)

Total suspended solid used as a parameter to measure the sediment trapping after flow through the vegetation zone. Based on Figure 13, The increment percentage of Total Suspended Solid (TSS) value from slow to fast velocity were within 13.04% to 36.11% for vegetation density of 1056 \( m^{-2} \). Next, for vegetation density of 1533 \( m^{-2} \), the increment percentage of Total Suspended Solid (TSS) value from slow to fast velocity were within 5.55% to 5.26%. Lastly, for vegetation density of 2756 \( m^{-2} \), the increment percentage of Total Suspended Solid (TSS) value from slow to fast velocity were within 6.67% and 6.25%. The increment is not stable between three type of vegetation density due to of inflow velocity. Total Suspended Solid (TSS) is found to be low at slow velocity because the sediment have longer time to settle to the channel bed.
4. Conclusion

The velocity of vegetation and upper layer of submerged vegetation. Three type of velocity were performed on three different of vegetation density. The profile velocity had been plotted versus water depth. It is found that the velocity at vegetation layer is lower compared to upper layer. Besides, the velocity of vegetation and upper layer is analyzed by using previous researcher’s equation and had compared with measured data in this study. The most suitable equation to be used in this experiment can be concluded through the graph of estimated versus measured and Root Mean Square Error (RMSE).

For a vegetation density, \( m = 1056 \ m^{-2} \), equation provide by Cheng [3] gives better accuracy with the lowest RMSE of 0.039 at vegetation layer. Whereas, Yang and Choi [13]gives better performance at upper layer with the lowest RMSE of 0.157. Yang and Choi [13]equation is found to be most suitable to be used with lowest RMSE of 0.045 and 0.124 at vegetation and upper layer respectively for a vegetation density, \( m = 1533 \ m^{-2} \). Meanwhile, for a vegetation density, \( m = 2756 \ m^{-2} \), Yang and Choi [13] show the best performance for both vegetation and upper layer with lowest RMSE of 0.142 and 0.087 respectively.

Global flow resistance is directly proportional to the velocity. In other words, flow resistance will increase when flow velocity increase. The graph of estimated against measured is plotted in order to determine the most suitable equation of previous researchers. Based on the result obtained, equation by Stone & Shen [15] is most suitable for density, \( m = 1056 \) and 1533 \( m^{-2} \) with RMSE of 3.062 and 1.732 respectively. But for density, \( m = 2756 \ m^{-2} \), Cheng [3] exhibits better performance with lowest RMSE of 1.051.

In term of the relationship between Total Suspended Solid (TSS) with flow velocity and vegetation density by using three different velocity and vegetation density, it is found that the slower the velocity, the higher the sediment compared to fast velocity. This is because slow velocity lengthens the time of sediment to settle down to the flume bed. While, in term of vegetation density, higher density trapped more sediment compare to lower density. This is due to short space to sediment to pass through the vegetation zone.

5. References

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**Notation**

| Symbol | Description |
|--------|-------------|
| $A$    | weight of filter and aluminium tray + residue in mg. |
| $B$    | weight of filter and aluminium tray in mg. |
| $C$    | volume of sample filtered in mL |
| $C_r$  | global flow resistance coefficient |
| $d$    | diameter of stick |
| $h$    | water depth |
| $i_b$  | slope of the channel |
| $m$    | vegetation density |
| $N$    | sample size |
| $s$    | spacing between vegetation |
| $v$    | flow velocity |
| $x_{ei}$ | estimated values |
| $x_{oi}$ | observed values |
| $z$    | water depth |