Jurnal
Teknologi

Full Paper

THE HYDRODYNAMIC CHARACTERISTICS FOR VEGETATIVE CHANNEL WITH GRAVEL BED DUNES

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Article history
Received
19 May 2021
Received in revised form
15 November 2021
Accepted
28 November 2021
Published Online
21 February 2022

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Graphical abstract

Abstract

Aquatic plants are known to provide flow resistance and impact the turbulence intensity and turbulent kinetic energy within the vegetated area. This paper further investigates the impact of both vegetation and dunes in open channels to the hydrodynamic characteristic of flow. Emergent vegetations were built from rigid wooden rod in staggered arrangement with 0.5% vegetations density were applied in the flume. Experiments were conducted with flow rate of 0.0058 m^3/s throughout the experiments. Dunes were constructed from gravel of 2 mm size diameter in the shape of standing waves of three different lee slope angles of 3°, 6° and 9°. Flow velocities are measured by using a velocimeter to get the raw data for the three-dimensional flow velocity in the x, y, and z directions. The velocities data were then analysed to calculate the mean velocity, turbulence intensity and turbulent kinetic energy. Experimental results showed that, for all three lee slope angles presented higher flow velocity in the vegetated channel compared to the non-vegetated channel. It was also found that greater lee slope angle dunes generate higher velocity for both channels with and without vegetation. Higher turbulence intensity can be found near the bed area and greater turbulence intensity also shown in the positive slope of a dunes compared to negative slope area. Higher turbulent kinetic energy values were recorded within the vegetated channel compared to the non-vegetated channels. As steeper dunes, the turbulence kinetic energy became greater, where the maximum value is recorded over the second crest near the free surface.

Keywords: Hydrodynamic, vegetative channel flow, dunes bed flow, turbulence intensity, turbulence kinetic energy time video

Abstrak

Tumbuhan akuatik diketahui mengenakan rintangan kepada aliran dan memberi impak kepada intensiti gelora dan tenaga kinetik gelora dalam kawasan bertumbuhan tersebut. Kertas ini selanjutnya mengkaji kesan kedua-dua tumbuhan dan gumuk terhadap pencirian hidrodinamik aliran dalam saluran terbuka. Tumbuhan muncul dibina daripada kayu rod tegar dalam susunan secara bersilang dengan kepadatan tumbuhan sebanyak 0.5% dalam flum. Kajian dijalankan dengan kadar alir sebanyak 0.0058 m3/s untuk seluruh uji kaji. Gumuk dibina daripada batu kerikil berdiameter 2 mm berbentuk gelombang dengan tiga sudut lee berbeza iaitu 3, 6 dan 9. Halaju air direkod menggunakan velocimeter untuk memperoleh data mentah halaju aliran tiga dimensi pada arah x, y dan z. Data kemudian dianalisis untuk mengukur purata halaju, keamatan gelora dan tenaga kinetik gelora. Keputusan kajian menunjukkan bagi ketiga-tiga sudut lee memberikan bacaan halaju yang lebih tinggi dalam saluran bertumbuhan jika dibandingkan dengan saluran tanpa tumbuhan. Selain itu turut didapati, semakin tinggi sudut lee gumuk menghasilkan halaju yang lebih tinggi untuk kedua-dua jenis saluran bertumbuhan dan tanpa tumbuhan. Keamatan gelora yang tinggi didapati pada kawasan yang menghampiri dengan dasar.

84:2 (2022) 93–102 | https://journals.utm.my/jurnalteknologi | eISSN 2180–3722 | DOI: https://doi.org/10.11113/jurnalteknologi.v84.17045 |

Keamatan gelora juga didapati tinggi pada kawasan cerun positif gumuk berbanding dengan kawasan cerun menurun. Nilai tenaga kinetik gelora yang lebih tinggi direkod dalam saluran bertumbuhan berbanding dengan saluran tanpa tumbuhan.

Kata kunci: Hidrodinamik, aliran saluran bertumbuhan, aliran dasar bergumuk, keamatan gelora, tenaga kinetik gelora

1.0 INTRODUCTION

Vegetative channels are known to stabilise the riverbank, reduce the erosion impact, turbidity, and flood control. The presence of vegetation is also known to cause resistance and reduces the flow velocity [3] and conveyance capacity [20]. Sedimentation that occurred on the bed of the river producing a conducive ecosystem for vegetation to grow. These plants grow naturally in the channel and are very important to aquatic life by supplying oxygen and removing excess nutrients to the ecosystem [1].

In the past, engineers implemented rapid disposal of surface runoff as not the best solution by changing the morphology of the river into concrete that transforms the natural functioning of the river as a perfect aquatic ecosystem. This conventional approach is possible to contribute to flash flood at the downstream due to high current flow compared to unbearable concrete channel capacity. Concrete channel resulting imbalance to hydrologic cycle where all the surface runoff to be channelled to concrete lining for rapid flow to the sea. However, vegetation also can reduce the water flow in the river and cause floods due to bottleneck effect at the downstream [14].

Vegetation plays a critical role to act as resistant towards the water flow by producing more turbulence to reduce the mean flow energy [17]. In the river, most of the emergent vegetation grows along the riverbank. The presence of aquatic plants causes higher drag force compared to the non-vegetative area. The flow from upstream will be diverted away from the vegetation area. Shear layer with vortices developed along the side between vegetative and non-vegetative areas. These vortices dominantly control the mass and momentum exchange [18], [23].

The other main component in the river that can alter the flow behaviour is the bed sediment. The distribution size of sediment along the river depends on the chemical and physical properties of the soil, and erosion and sediment transport by overland flow. Gravel is commonly found in upstream areas of the riverbed that have low to medium sediment transport rate [15]. The effect of the gravel bed surface towards turbulence is important to estimate the friction factor and coarse grain size sediment transport. River flow near the bed surface collides with coarse size particles that can change the mean velocity and turbulence characteristics of the flow [5], [8]

The focus of this paper is to study the characteristic of flow through vegetation with low angle dunes. Kwoll *et al*. [10] present an experimental research of flow structure and resistance over 10, 20 and 30-degree dunes. Results show that lower magnitude of turbulence production for gentle lee slope due to decrease in velocity gradient. Analyses of results show that flow resistance of dunes decreases down the slope at lee. According to Kwoll *et al*. [10] dunes with lee slope angle less than 30 degree are categorised as low-angle dunes. Kabiri *et al*. [9] carried out a laboratory work using flume to measure flow velocity, turbulence intensity and Reynolds stress over a wavy bed with vegetation cover. Vegetation used in this research is like grass covering the fixed dunes of 30-degree lee slope angle. The log law for velocity profile is not valid for flow within the vegetation, but it can be applied from the top of vegetation cover within the inner layer. The flow structure separates at the crest generates a shear layer which is crucial in the transport of momentum and energy.

The presence of both vegetation and low angle dunes might produce differ explanations. As study carried out by Afzalimehr *et al*. [2] on the field, the formation of a new boundary layer is caused by a transition in bed roughness from non-vegetative gravel bed to gravel bed with vegetation. The velocity profiles over vegetated and non-vegetated bedforms vary because of this new boundary layer. The vegetative channel velocity profile indicates s-shape over the stoss area with gravel bed. Nonetheless, the velocity distribution over the crest area is identical between non-vegetative and vegetative with gravel bed. The development of S-shape distribution may be caused by multiple reasons. Wake turbulence from the roughness element is one of them while vegetation existence would be the second. Others, the condition of bedforms can determine the bigger scale roughness. There is still a demand to understand the hydrodynamic characteristics in vegetative with gravel dunes channel. The complexity of this study needs more explanation from various types and conditions of natural rivers. This paper may contribute better understanding for those parameters.

2.0 METHODOLOGY

Experimental runs were conducted in the Hydraulics Laboratory, Department of Civil and Structural Engineering in UKM. The laboratory works were divided into two parts which include model instrument preparation and experiment implementation.

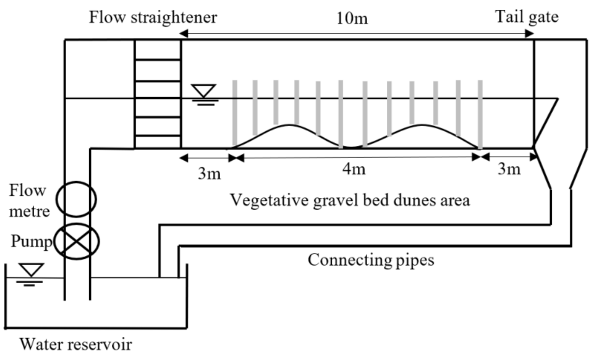


Figure 1 Schematic diagram of the experimental setup

Experimental works were conducted in a recirculating flume, as shown in Figure 1, with dimensions of 10 metres long, 0.5 metres width and 0.45 metres height. The steel made flume structure, equipped with a tail gate at the end permits an adjustment of water level, and a flow meter to regulate the flow into the flow. The wall is made of transparent fibres, assisting in the construction of the grave bed dunes and experimental observations. A stack of cylindrical PVC pipes, with diameter 0.0254 metres and 0.4 metres length, acting as the flow straightener (and reducing turbulence intensities) was installed at the flume inlet.

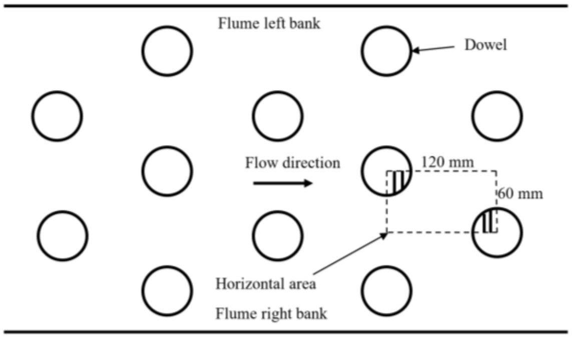


Figure 2 Vegetation density according to solid volume fraction (SVF)

To simulate vegetation conditions, an acrylic perforated panel with dimension of 0.5 m x 4 m is placed on the flume floor. Each perforation has a diameter of 10 mm, and was organised as staggered holes, whereby the distance between each hole is 50 mm. Vegetative models with rigid characteristics are made from wooden rods that have 10 mm diameter and 0.4 metres length. The rods are installed on the panel manually using a hammer to securely fit the rod into hole. The pattern of vegetation arrangement is staggered where it simulated the on-site sparsely grown aquatic plant [11]. Figure 2 illustrate the vegetation density that was determined by using the solid volume fraction method SVF = $m\pi d^2/4$, where m = fraction of wooden rods area. The concept is the total area wooden rods cover is divided by the horizontal area. The density of vegetation is set as 0.005.

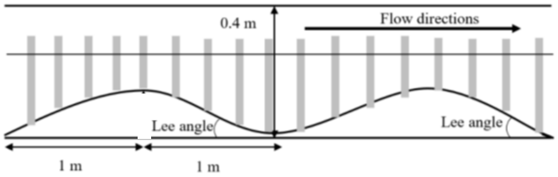


Figure 3 Standing waves dunes where wooden rods are placed from lee-to-lee dunes

Once the acrylic panel and the rods are installed, the gravels are placed between the wooden rod by using a scoop and distributed evenly across the flume (and the acrylic panel) as the base. The gravel then was carefully placed to imitate dunes. Standing waves dunes have been chosen in the study that have the same even angle on both sides of the lees. The gravel bed dunes were constructed 6 metres away from the inlet chamber, whereby at this location, preliminary velocity measurement confirmed a fully developed steady flow. Dunes are built using homogeneous mean diameter gravel of 20 millimetres. Gravel was chosen as the bed material to ensure no inception of sediment motion throughout all experiments especially at higher angles of dunes [7]. The dunes were designed to be at three different angles, 3°, 6° and 9°. The study paid attention to low dune angles, to imitate real fluvial environments, where less than 30° are considered as low angles with more reflecting to the real world [10]. The dunes were laid down by fixing the distance between the lee to crest as 1 metre and the width of a dune is 2 metres (as represented in Figure 3). Based on the width, the height of the dune for each angle was calculated using the simple trigonometry equation giving height of 0.052 m, 0.105 m, 0.158 m for 3°, 6° and 9°, respectively. To assist in the construction of the dune, particularly to ensure an accurate angle, a rope indicating the hypotenuse (of the associated angles) was glued to the flume wall. Two dunes with a total length of 4 metres made up the working area.

Once the construction of vegetated gravel bed dunes is done, the pump is switched on allowing flow entering the flume at a constant discharge of 0.006 m^3/s. The principle of mass stated that, for a steady flow, the mass flow rate into the volume must equal the mass flow rate out. A steady flow velocity at 0.03 m/s throughout the experiments were achieved by dividing the flow rate to the wetted cross-sectional flow area. The tailgate is adjusted to provide a minimum water level of 10 centimetres, calculated from the crest of dunes. This essentially gives the water level of 400 mm, when measured from the lowest bed surface.

The three-dimensional flow velocity in the flume that was measured by using an Acoustic Doppler velocimetry (ADV). ADV used for this study is made by Nortek ADV from Norway. The purpose of the velocimeter is to transmit a short acoustic signal from the transmitter to a sample volume in 50 millimetres distance. The pulse will reflect to a receiver where this echo is recorded by four acoustic receivers [21]. These echoes later onto be processed in finding Doppler displacement where the scale is the same with the sound velocity in water. The instantaneous and fluctuating velocity are sent to a computer in the laboratory for post laboratory analysis. The ADV is connected to a computer by wire and vectrino software showed the interface of the reading. Based on this application, the time to record the data can be adjusted to 1 minute for each sample. The raw data is extracted by using WinADV application where it converts the raw into simpler files that can be opened by Excel.

The measuring device is placed perpendicularly on the dedicated, adjustable 2D transverse system allowing an accurate point velocity measurement. The Vectrino records velocity measurement at uniform distances starting from the first dune's crest, brink, lee, leeward and ends at the second dune's crest, as shown in Table 1. At each longitudinal point, the velocity was measured at the mid flume, minimising, if not eliminating the side wall effect. The velocity meter measures 3D velocity, permitting an analysis in the streamwise (*x*), transverse (*y*) and vertical directions (*z*), where the streamwise velocity is expected to play a greater role. There are five vertical points from the dune surface until flow surface, labelled as z_1, z_2, z_3, z_4 and z_5. The distances of vertical sampling points were set close to the dunes surface and became more distant to upward. This is due to critical conditions where the changes of flow are significant.

Table 1 Measurement velocity points at the longitudinal direction

Points	X_1	X_2	X_3	X_4	X_5
Distance (m)	0	0.4	1.0	1.6	2.0
Explanation	First Crest	Brink	Lee	Leeward	Second crest

There are six experiments total carried out for this study with three low angle dunes for vegetative and non-vegetative channels. Table 1 presents the location of velocity sampling in longitudinal direction starting over the first crest until the peak of the second crest.

Figure 4 illustrates the sampling locations from plan to side views. The first point is the first crest which is clearly located in between two wooden rods. This is the same goes to the brink and contradicts to others location condition in front of wooden rods. For each longitudinal sampling point, there are 5 vertical points of velocity recorded. Moving upward, the first three points are close to each other while the rest is a little bit further. The reason is near bed especially gravel bed dunes considered the critical area as turbulence might happen there.

The dunes angles are determined by the lee angle for 3°, 6° and 9° respectively. For the post processing of data obtained from the ADV, a three-dimensional coordinate system has been adopted where *x*, *y*, and *z* denoted streamwise, transverse and vertical directions, respectively. Spike filtering, correlation, and signal-to-noise ratio (SNR) thresholding techniques were used as suggested by Chanson *et al.* [4] to minimize the effect of the Doppler noise in the data. To further improve the accuracy of the turbulence measurements, low correlations and low SNR data were removed. The spikes in velocity measurements removed from the raw time series were replaced by applying cubic polynomial interpolation. The number of interpolated points consisted less than 5% of the original velocity record and had no effect on the spectrum and overall frequency content [12].

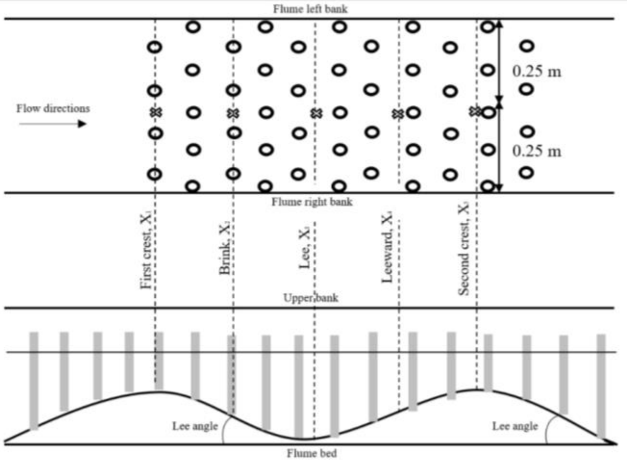


Figure 4 Sampling location

The ADV provides an instantaneous 3D velocity measurement U at *x*, *y*, *z*. Using the Reynolds decomposition, the turbulent fluctuating components u' can be separated using $U = \underline{U} + u'$ where $\underline{U}$ denotes the mean flow velocity, calculated as the temporally averaged. The vertical velocity profiles at near-dune bed were described in terms of the mean velocity components for streamwise ($\underline{U}$), transversal ($\underline{V}$) and vertical ($\underline{W}$).

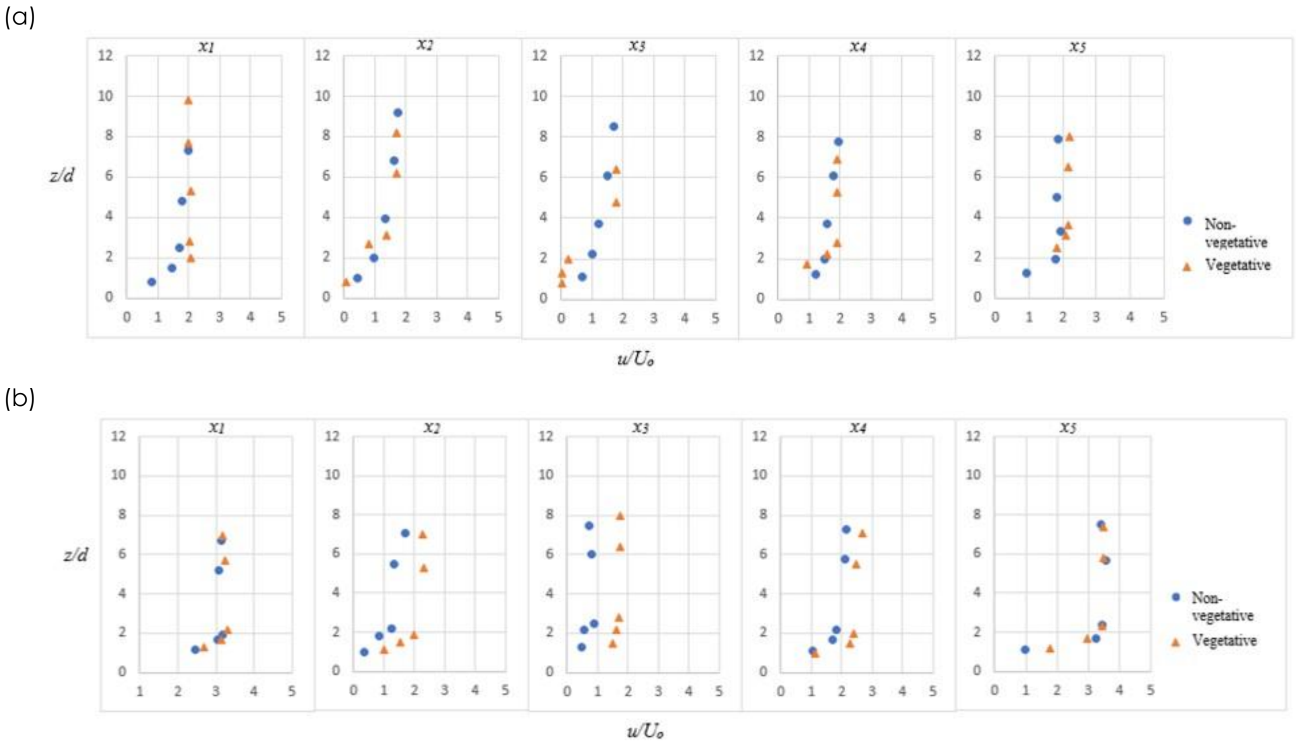
To illustrate the turbulence strength, the turbulence intensity was presented based on the root-mean-square (r.m.s) velocities as $\sqrt{u'^2}/U$. As 3D velocity measurement is available, the turbulence intensity was presented for horizontal (u), transversal (v) and vertical (w).

The turbulent kinetic energy (TKE) is one of the main variables in this experiment. The energy is presented by the strongness indirectly produced by the turbulence in the flow. Turbulence Kinetic Energy (TKE) was then calculated as $TKE = 1/2(u'^2+v'^2+w'^2)$ at each longitudinal and vertical point.

3.0 RESULTS AND DISCUSSIONS

The determination of the flow either laminar or turbulence is important in applying fluid mechanics. In any circumstances, Reynolds number is an equation that can distinguish between laminar and turbulent flow. For open channel, the flow is described as laminar if Reynolds number is less than 500 and turbulent greater than 12 500. The flow with the value in between 500 to 12 500 might represent both laminar and turbulence that depends on the morphological of the channel. In this study, the Reynolds number is calculated as $Re=U_{\circ}l/\upsilon$ where $U_{\circ}$= flow velocity, l = hydraulic radius and υ = kinematic viscosity of water at room temperature ($\upsilon = 0.8007\times10^{-6}$ m²/s, 30°c). The value is 4163 which the flow can be categorised as transitional between laminar and turbulent. The flow also be viewed in different perspective such as Froude Number, $Fr= U_{\circ}/\sqrt{gd}$ where, g=gravitational acceleration and d=flow depth. When Fr is less than 1, the flow is subcritical meanwhile if Fr is equal to 1, the flow is in critical conditions. The value indicates greater than 1 will describe the flow in supercritical conditions. The Froude number for this study is described as less than 1 with 1.51×10^{-2}

This section describes the turbulence characteristic within the sparsely vegetated area above gravel bed dunes. The mean velocity profiles near bed dune will be first discussed.



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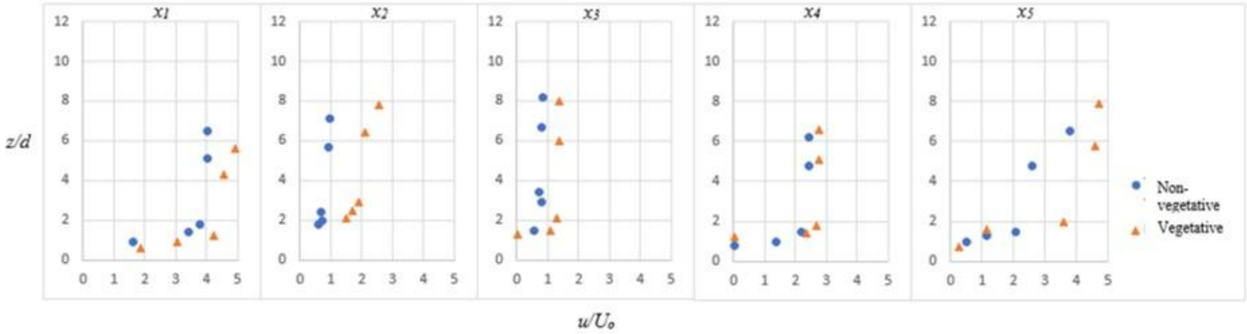

Figure 4 Velocity profile for dunes angle (a) 3° ; (b) 6°; (c) 9°

Figure 4 shows the similar log distribution pattern of non-dimensional time-average velocity vectors profile for all dunes angles where U_o = Cross-sectional average velocity. More likely, the cross-sectional average velocity is calculated based on the inlet flow rate before entering vegetated dunes region. u = mean velocity is time average velocity taken from each point of velocity sampling for one minute. There is a slightly greater flow velocity for vegetative channel due to the sample locations located in between two wooden rods. According to Nepf [16], as the flow passes through the wooden rod, it generates vortices and wakes. In between two wooden rods, a shear layer is developed as pressure is higher behind rods that makes different velocity occur. In overall perspective, the crests and leeward illustrate different maximum velocity profiles as the angle goes steeper.

At 3° angle, x_1 (as shown in Figure 4) represents the first crest reading where the non-vegetative channel indicates approximately similar and slightly lower velocity except $z/d < 3$ due to roughness of the bed shear stress from the gravels. According to Dey *et al*. [6] as the flow approaches the bed, the pressure also developed that caused change in velocity gradient and reduces the flow velocity. The vegetative channel resulting in higher value of velocity at all elevations might prove the presence of wooden rod makes the flow in between higher. The rods create resistance that contribute wakes formation at downstream causing gradient in spatial velocity distributions. As the flow moves to the brink, the velocity is depleted as the new boundary layer occurs from the faster and slower fluid movement of wakes. The flow separation starts at the crest to further sudden expansion downstream resulting in a circulation area formed in clockwise manners. Lee velocity proves that as the vortices become bigger from the magnitude of different fluid movement from vegetation to dunes. The velocity is developed again as the flow moving toward the leeward side and peaks at the second crest. The difference between vegetative and non-vegetative are not significant.

For 6° angle, the values between vegetative and non-vegetative are not significant at the first and second crests although the velocity at the second crests is greater than the first one. Vegetative channel shows higher velocity at the brink as resultant of shear flow between two vortices transversely from wooden rod and longitudinally from dunes. Nepf [17] describes the von Karman vortex street only appears at a certain length behind the wooden rod. Since the arrangement of the wooden rods is staggered, this may explain the result of the previous statement. The velocity is relatively slower for both vegetative and non-vegetative at all elevations at lee. Wooden rod resistance makes the flow in vegetative slower.

At the highest dunes angle of 9°, vegetative velocity shows slightly greater values at all locations and elevations with significance at the brink. The understanding from this situation can be given as the gravitational potential energy might be considered from steeper dunes by forming a solid shear layer that is critical for momentum and energy transfer as well as the formation of coherent structures that are based on Kabiri *et al*. [9] findings. The values at $z/d < 3$ for both crests are corresponding between the channels but as it goes higher to the free space, the velocity is greater. According to Dey *et al*. [6], In the flow over a dunal bed, it causes the so-called kolk-boil effect. The kolk-boil is a large-scale vortex caused by a split vortex behind the dune crest, which moves to the next brink side before spreading upward. The faster-moving fluid zone begins at the dune's stoss side, moves closely along the dune's edge, and then turns toward the free surface. The second crest has notably higher values where s-shape is noticeably formed. Study by Afzalimehr *et al*. [2] informs the variations in velocity over vegetative covered gravel bedform are far greater than those over a gravel bedform without vegetation. Illustrating the effect of vegetation on the boundary layer's outer zone.

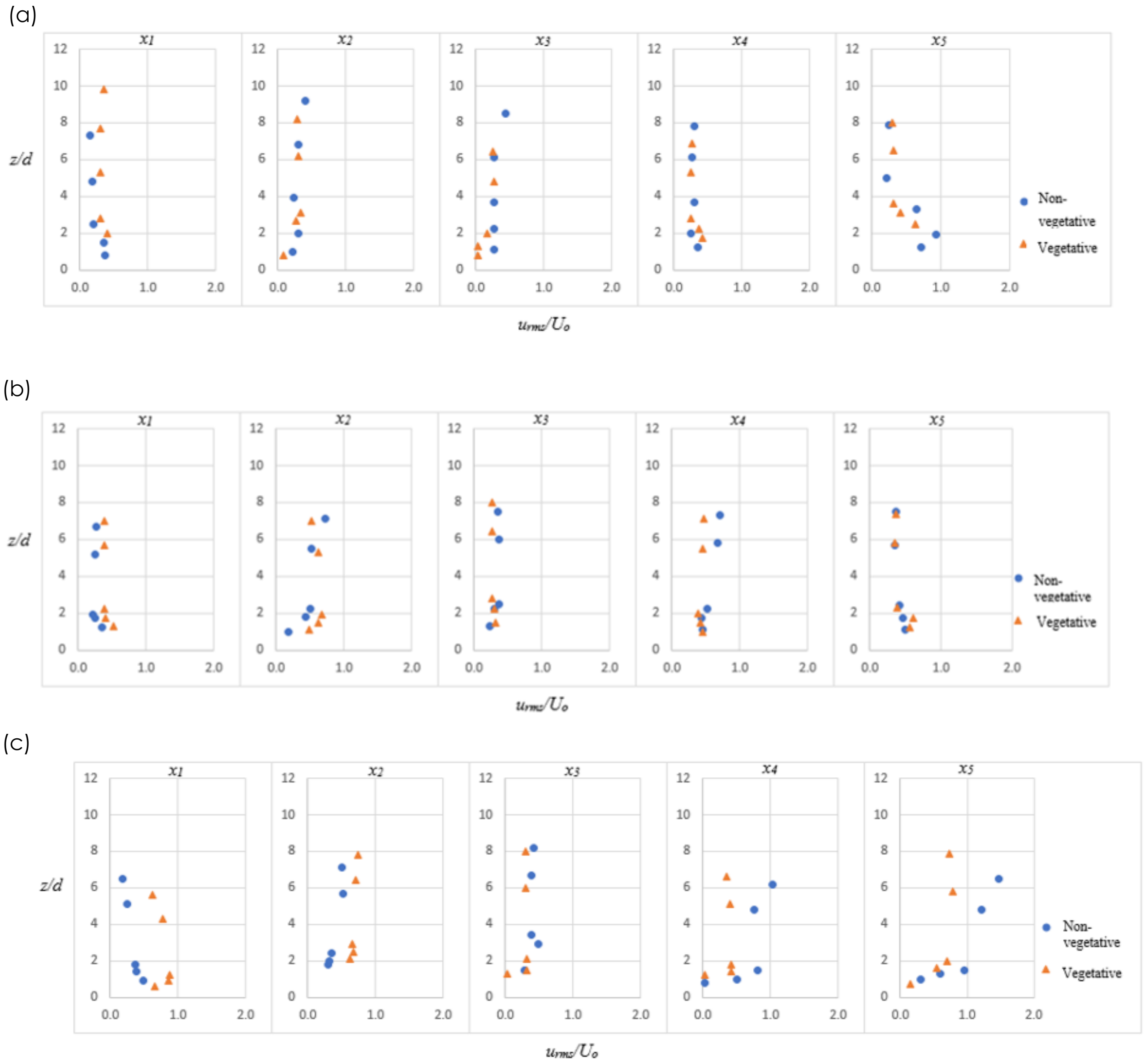

Figure 5 Turbulence intensity for dunes angle (a) 3°; (b) 6°; (c) 9°

Based on Figure 5, the dimensionless values for turbulence intensity are represented by U_{rms} with factor of U_o, initial average stream flow velocity. The turbulence intensities profile in Figure 5 suggested the turbulence intensity is heavily influenced by characteristics of bedforms and the presence of vegetation. In other ways, the sampling locations also play the vital role in choreographing the turbulence intensity readings. The turbulence intensities pattern in both vegetated and non-vegetated channels represent declines in directions of the flow. Study by Zhang *et al*. [22] also resulted in the same manner as for vegetated unvarying bedforms.

At 3° angles, turbulence intensity is almost uniform at all locations and elevation except z/d < 4 at the second crest. Near bed regions manifest turbulence intensity occurs for both channels (with and without vegetation). This might be due to the rough bed dunes surface by 2 mm gravels which have more irregular shape and produce wake vortices. This activity might consider erosion happened during the experiment [2]

At 6° angles, turbulence intensity is substantial at the brink and lee ward as these locations where the wakes begin to develop and lose. It is observed at depth z/d<3, the turning point of the turbulence intensity decreasing as upward directions. This means that the Kelvin-Helmholtz instability is causing massive coherent vortices to form Afzalimehr *et al*. [2]. At lee, the intensity is lowest that proves the wakes are bigger and uniform. Near bed regions at the crests indicates turbulence intensity activity happened.

For 9° dunes angles, the difference of turbulence intensity between vegetative and non-vegetative are remarkable. The values are higher for vegetative at the first crest, brink and lee that contradicts leeward and second crest where the reading represents non-vegetative channel has the greater values. This situation might give explanation to the sparse vegetation arrangement. Furthermore, Afzalimehr *et al.* [2] explained that this zone experiences an accelerating flow phase, while the lee side experiences a decelerating flow process. Steeper the dunes angle provides more dynamic to the turbulence intensity reading.

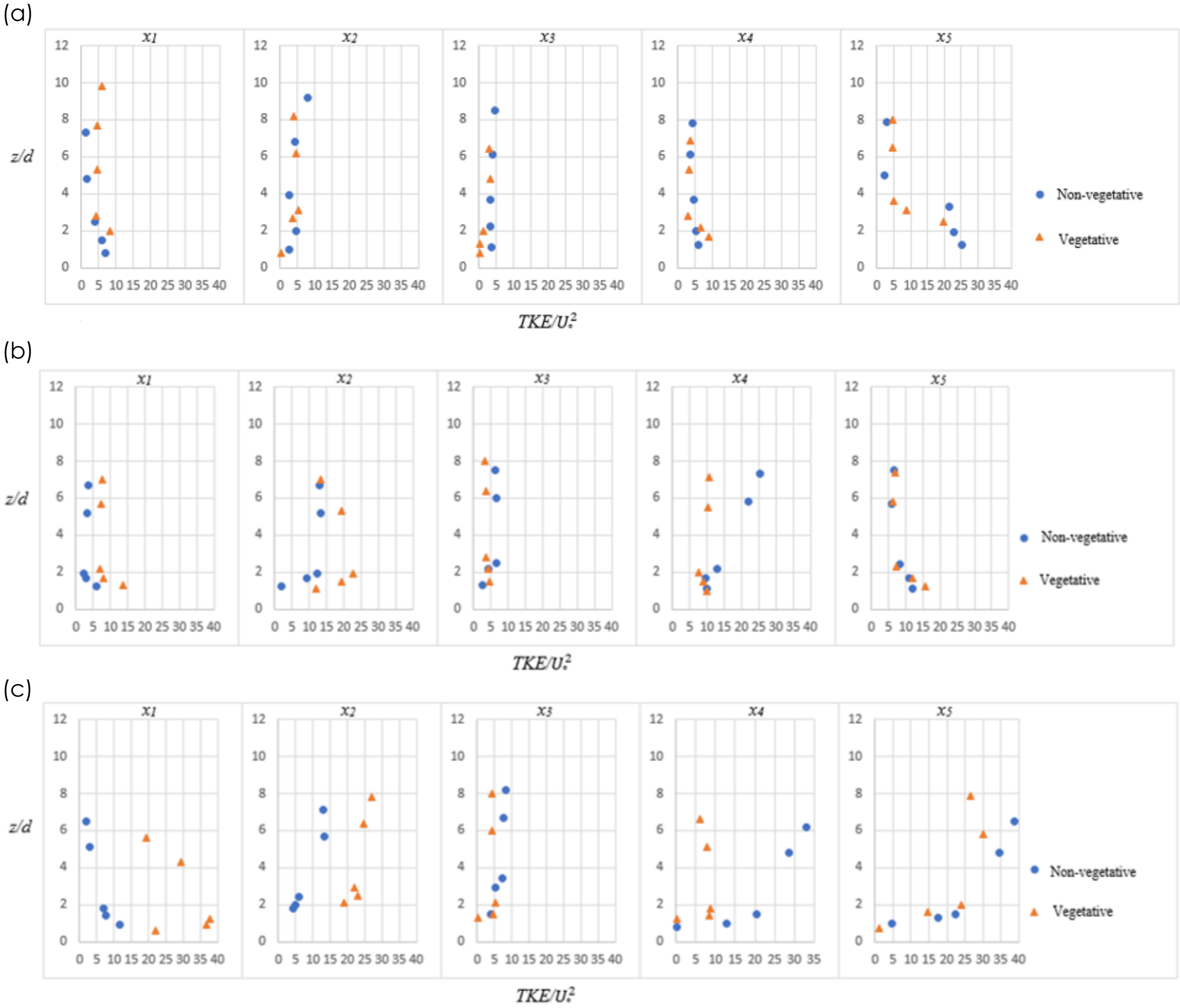

Figure 6 Turbulence kinetic energy for dunes angle (a) 3°; (b) 6°; (c) 9°

According to Figure 6, the dimensionless turbulence kinetic energy is recorded by division to square of initial cross-sectional average velocity in flow over vegetated and non-vegetated gravel dunes. Turbulence kinetic energy is a parameter in which to appreciate the energy produced by eddies in turbulent flow per unit mass. Applying Reynolds-averaged Navier Stokes equation, it can be characterized as root-mean-square velocity fluctuation in the flow. 3° degree dunes angle presents potential turbulence kinetic energy at the bed near regions at the second crest. Increasing elevation to the crest creates resistance consequence to the flow and generates induced sub-layer from head flow layer. Dey *et al.* [6] implies the separation of shear layer happens where large-scale eddies formed towards the head flow layer from Kelvin-Helmholtz instabilities. The rest locations indicate no impacts as also for both vegetative and non-vegetative channels. Since this study is conducted with low solid volume fraction φ = 0.005, it is comparable to Union & Published [19] with φ = 0.005 establishing the turbulence proportion the same for both vegetative and non-vegetative channels. The irregular surface of gravel bed dunes with concentration between wakes produced by wooden rods might contribute to the greater energy. As the dunes are steeper with 6° degree angles, the turbulence kinetic energy is more noticeable at the bottom near bed region for all locations. Over the first crest and brink, TKE is higher for vegetative channels near bed region and as the elevation is higher up to free water space, the value is united between vegetative and non-vegetative channels. This precedence statement is compared to lower angle dunes, the TKE are much the same for both channels. The explanation behind this phenomenon is the TKE values are more impacted from steeper dune angles and presence of vegetation not significantly contributed. Findings from Maji *et al*. [13], the immensity of the rate of production of TKE is greater in the wake region and weaker values were recorded in between two wooden rods from sturdy local accelerations in the flow. Both the first crest and brink sampling locations are in between rods. The lee reading shows the least energy as the wakes lose energy down the dunes. The presence of vegetation does give impact to the turbulence kinetic energy from the combination of eddies and wakes formed from vertical to transverse directions.

The steepest dunes angles of 9°, turbulence kinetic energy is higher at the first crest and brink. Energy is concentrated at the lower near bed regions for the first crest. The brink readings as the elevation goes higher, the energy is proportionally higher too. Steeper dunes rather give impact to the energy as downing the dunes, potential gravitational energy can be considered. Non-vegetative is higher at the leeward compared to vegetative channel proves the wooden rod presence would dissipate the energy.

4.0 CONCLUSION

Presence of vegetation causes higher value in velocity due to overlapping of vortices created by the individual wooden rod. Higher velocity occurs at the first crest and becomes slower when approaching the lee section. As the flow moved towards the second crest the velocity became higher again and it was found that the velocity at the first crest is lesser compared to the second crest velocity. At the bed surface region, the velocity is slower because of the rough surface created by the gravel dunes. Experimental results also show that increase in angle of dunes increases the average velocity of the flow.

Analyses for turbulence intensity show that the vegetated channel generated more turbulence from the first crest to the brink area. The magnitude of turbulence from the first lee to the second crest is greater for the non-vegetated channel. Most of the turbulence occurred at the bed region due to higher average velocity. The vertical points $z/d > 5$ showed uniform pattern of turbulence intensity because this region is less affected by dunes and more affected from the average channel flow. The second crest shows the value and pattern are almost the same for both channels.

Similarly, turbulence kinetic energy (TKE) is more prominent near the bed of dunes. The energy is greater at the downslope of dunes for vegetated channel. On the side of the increasing slope of the dunes, the value of TKE was found to be lesser compared to the non-vegetated channel. The second crest has the highest TKE followed by the first crest and the lee region.

Acknowledgement

The authors acknowledge the financial support given by the Ministry of Higher Education through the Fundamental Research Grant Scheme FRGS/1/2017/TK01/UKM/03/1 Ministry of Higher Education (MOHE) and Universiti Sains Malaysia for the approved fund which makes this important research viable and effective.

References

[1] Afzalimehr, H., Maddahi, M. R., & Sui, J. 2017. Bedform Characteristics in a Gravel-bed River. *Journal of Hydrology and Hydromechanics*. 65(4): 366-377. DOI: https://doi.org/10.1515/johh-2017-0023.

[2] Afzalimehr, H., Maddahi, M. R., Sui, J., & Rahimpour, M. 2019. Impacts of Vegetation Over Bedforms on Flow Characteristics in Gravel-bed Rivers. *Journal of Hydrodynamics*. 31(5): 986-998. DOI: https://doi.org/10.1007/s42241-019-0053-x.

[3] Aliza Ahmad, N., Ali, Z. M., Mohd Arish, N. A., Mat Daud, A. M., & Amirah Alias, N. F. 2018. Determination of Flow Resistance Coefficient for Vegetation in Open Channel: Laboratory Study. *IOP Conference Series: Earth and Environmental Science*. 140(1): 0-7. DOI: https://doi.org/10.1088/1755-1315/140/1/012019.

[4] Chanson, H., Trevethan, M., & Aoki, S. 2008. *Acoustic Doppler Velocimetry (ADV) in Small Estuary: Field Experience and Signal Post-Processing*. 19: 307-313. DOI: https://doi.org/10.1016/j.flowmeasinst.2008.03.003.

[5] Dehsorkhi, E. N., Afzalimehr, H., Gallichand, J., & Rousseau, A. N. 2013. Turbulence Measurements above Sharp-crested Gravel Bedforms. *International Journal of Hydraulic Engineering*. 2(5): 101-114. DOI: https://doi.org/10.5923/j.ijhe.20130205.04.

[6] Dey, S., Paul, P., Fang, H., & Padhi, E. 2020. Hydrodynamics of Flow Over Two-dimensional Dunes. *Physics of Fluids*. 32(2). DOI: https://doi.org/10.1063/1.5144552.

[7] Ghoshal, K., & Pal, D. 2014. Grain-size Distribution in Suspension Over a Sand-gravel Bed in Open Channel Flow. *International Journal of Sediment Research*. 29(2): 184-194. DOI: https://doi.org/10.1016/S1001-6279(14)60035-4.

[8] Gualtieri, C. 2016. Hydrodynamics and Transverse Mixing in a Rectangular Channel with Bed Forms and Bank Vegetation. *8th International Congress on Environmental Modelling and Software, Toulouse, France*. July 12.

[9] Kabiri, F., Afzalimehr, H., & Sui, J. 2017. Flow Structure Over a Wavy Bed with Vegetation Cover. *International Journal of Sediment Research*. 32(2): 186-194. DOI: https://doi.org/10.1016/j.ijsrc.2016.07.004.

[10] Kwoll, E., Venditti, J. G., Bradley, R. W., & Winter, C. 2016. *Journal of Geophysical Research: Earth Surface*. 121(3): 545-564.
DOI: https://doi.org/10.1002/2015JF003637.

[11] Liu, D., Diplas, P., Fairbanks, J. D., & Hodges, C. C. 2008. An Experimental Study of Flow through Rigid Vegetation. *Journal of Geophysical Research: Earth Surface*. 113(4): 1-16.
DOI: https://doi.org/10.1029/2008JF001042.

[12] Maji, S, Pal, D., Hanmaiahgari, P. R., & Pu, J. H. 2016. *Phenomenological Features of Turbulent Hydrodynamics in Sparsely Vegetated Open Channel Flow*. 9(6): 2865-2875.
DOI:10.29252/jafm.09.06.26202.

[13] Maji, Soumen, Hanmaiahgari, P. R., Balachandar, R., Pu, J. H., Ricardo, A. M., & Ferreira, R. M. L. 2020. A Review on Hydrodynamics of Free Surface Flows in Emergent Vegetated Channels. *Water (Switzerland)*. 12(4): 1-17.
DOI https://doi.org/10.3390/W12041218.

[14] Miyab, N. M., Afzalimehr, H., & Singh, V. P. 2015. Experimental Investigation of Influence of Vegetation on Flow Turbulence. *International Journal of Hydraulic Engineering*. 4(3): 54-69.
DOI: https://doi.org/10.5923/j.ijhe.20150403.02.

[15] Mohtar, W. H. M. W., Bassa, S. A., & Porhemmat, M. 2017. Grain Size Analysis of Surface Fluvial Sediments in Rivers in Kelantan, Malaysia. *Sains Malaysiana*. 46(5): 685-693.
DOI: https://doi.org/10.17576/jsm-2017-4605-02.

[16] Nepf, H M. 2004. Vegetated Flow Dynamics Introduction: Scales of Morphology and Flow in a Tidal Marsh. *The Ecogeomorphology of Tidal Marshes*. 59.
DOI: https://doi.org/10.1029/CE059p0137.

[17] Nepf, Heidi M. 2012. Hydrodynamics of Vegetated Channels Hydrodynamics of Vegetated Channels. *Journal of Hydraulic Research*. 50(3): 262-279.
DOI: https://doi.org/10.1080/00221686.2012.696559.

[18] Stoesser, T., Asce, M., Kim, S. J., Diplas, P., & Asce, M. 2010. Turbulent Flow through Idealized Emergent Vegetation. *Journal of Hydraulic Engineering*. 136(12): 1003-1017.
DOI: https://doi.org/10.1061/(ASCE)HY.1943-7900.0000153.

[19] Caihong Tang, Jiarui Lei, Heidi M. Nepf. 2019. Impact of Vegetation-Generated Turbulence on the Critical, Near-Bed, Wave-Velocity for Sediment Resuspension. *Water Resources Research*. 55(7): 5904-5917.
DOI: https://doi.org/10.1029/2018WR024335.

[20] WU, W., & HE, Z. 2009. Effects of Vegetation on Flow Conveyance and Sediment Transport Capacity. *International Journal of Sediment Research*. 24(3): 247-259.
DOI: https://doi.org/10.1016/S1001-6279(10)60001-7.

[21] Zame, K. K. 2010. *ETD Program*. Youngstown State University, Department of Geological and Environmental Sciences.

[22] Zhang, H., Wang, Z., Dai, L., & Xu, W. 2015. Influence of Vegetation on Turbulence Characteristics and Reynolds Shear Stress in Partly Vegetated Channel. *Journal of Fluids Engineering, Transactions of the ASME*. 137(6): 1-8.
DOI: https://doi.org/10.1115/1.4029608.

[23] Zong, L., & Nepf, H. 2010. Flow and Deposition in and around a Finite Patch of Vegetation. *Geomorphology*. 116(3-4): 363-372.
DOI: https://doi.org/10.1016/j.geomorph.2009.11.020.