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Threshold Criteria of Sediment Motion for Biological Cohesive Sediment Mixture

(Kriteria Pergerakan Ambang Sedimen bagi Campuran Sedimen Jelekit Biologi)

Najwa Izzaty Muhammad Azha[a], Wan Hanna Melini Wan Mohtar[a,b]*
[a]Civil Engineering Programme,
[b]Smart and Sustainable Township Research Centre,
Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Bangi, Malaysia

ABSTRACT

Shields diagram is used as the main source to determine the incipient motion of sediment. However, incipient sediment motion in the Shields diagram was developed based on non-cohesive sediment where the parameter influencing the motion of cohesive and non-cohesive sediments are different. Therefore, this study attempts to investigate the incipient sediment motion for biological extracellular polymeric substance (EPS) influenced by a cohesive sediment mixture. Percentage of silt with a median grain size of 28 μm (which acts as the cohesive material) and fine sand with of 150 μm were varied as 10:90, 20:80, 40:60, and 50:50, which formed the cohesive sediment mixture. Two different concentrations of EPS 0.02% (which denotes as low concentration) and 0.1% (as high concentration) were well mixed with the sediment mixture. This study utilised Xanthan gum, which acts as a substitution for EPS. The experiments were conducted in a laboratory flume and the threshold criterion for sediment motion was obtained through observation. The critical Shields parameter was calculated using the critical shear velocity and root-mean-square horizontal velocity (representing turbulent fluctuations) when few of the particles on the bed was observed to move. Obvious finding from this study is the presence of EPS clearly influence the threshold criteria based on the higher value obtained at sediment mixture with 0.1% compared to the values found for the 0.02% EPS sediment mixture. The values of the critical Shields parameter were monotonously increased as the percentage of silt in the sediment mixture increases. The presence of silt in the sediment mixture increases the sediment stability signifying more hydrodynamic forces are required for the particles to be entrained. The critical Shields parameter obtained based on the critical shear velocity and turbulent fluctuations posed similar trend as described in the well-established Shields curve indicating that the velocity scale used to describe the incipient sediment motion is not a decisive factor.

Keywords: Incipient sediment motion; silt-sand-EPS mixture; biological cohesive sediment

ABSTRAK

Rajah Shields digunakan sebagai rujukan utama bagi menentukan pergerakan ambang sedimen. Namun begitu, pergerakan ambang sedimen di dalam rajah tersebut dibangunkan berdasarkan sedimen tidak jelekit sahaja, di mana parameter yang mempengaruhi pergerakan ambang sedimen bagi sedimen jelekit dan tidak jelekit adalah berbeza. Justeru itu, kajian ini bertujuan untuk mengkaji pergerakan ambang bagi sedimen jelekit dengan pengaruh bahan polimer ekstraselular (EPS). Peratusan kelodak dengan saiz median partikel ialah 28 μm (yang bertindak sebagai bahan jelekit) dan pasir halus bersaiz = 150 μm diubah sebagai 10:90, 20:80, 40:60, dan 50:50, yang membentuk campuran sedimen jelekit. Dua kepekatan EPS berbeza digunakan iaitu 0.02% (yang memberikan kepekatan rendah) dan 0.1% (kepekatan tinggi) dan digaulkan bersama campuran sedimen. Kajian ini menggunakan gam Xanthan mewakili EPS. Kajian dilakukan di dalam flum makmal dan kriteria ambang bagi pergerakan sedimen ditentukan melalui pemerhatian. Parameter Shields kritikal dikira dengan menggunakan halaju ricih kritikal dan halaju mendatar punca kuasa dua (memberikan gambaran perubahan gelora) iaitu halaju tercerap ketika beberapa partikel di atas dasar dilihat bergerak. Hasil nyata dari kajian ini ialah kehadiran EPS memberikan kesan kepada kriteria ambang berdasarkan peningkatan nilai yang diperolehi pada campuran sedimen jelekit dengan 0.1% EPS berbanding dengan nilai yang diperolehi untuk campuran sedimen 0.02% EPS. Nilai parameter kritikal Shields meningkat apabila peratusan kelodak di dalam campuran sedimen meningkat. Kehadiran kelodak di dalam campuran sedimen meningkatkan kestabilan sedimen menunjukkan lebih tinggi daya hidrodinamik yang diperlukan untuk menggerakkan sedimen. Parameter kritikal Shields yang diperolehi menggunakan halaju ricih kritikal dan perubahan gelora memberikan trend sama sepertimana profil Shields menunjukkan skala halaju yang digunakan untuk memerikan pergerakan ambang sedimen adalah faktor tidak penentu.

Kata kunci: Pergerakan ambang sedimen; campuran kelodak-pasir halus-EPS; sedimen jelekit biologi

INTRODUCTION

The movement of cohesive sediment is receiving attention abundant of engineering projects are constructed on the cohesive sediment. The determination of incipient sediment motion or threshold criteria is important to determine the stability of the riverbank, the movement of the remaining sediment from the mainland, bank erosion, directions, water quality evaluation, to name of a few. Bank erosion of cohesive sediments occurs as a mass failure, which is associated with the sediment's mechanical strength and is defined as the collapse of the bank material when the critical height and angle have been exceeded. Fluvial erosion occurred when bed materials are mobilized as a result of entrainment or dislodgement of individual cohesive particles or aggregates at the flow sediment interface due to flow shearing action (Papanicolau et al. 2007).

The threshold criteria of sediment motion describe the beginning of sediment movement or mobility from its previously stationary state. The flow velocity and the hydrodynamic forces acting on the particle sediment influence this phenomenon. When the turbulent flow runs over the sediment particles, the hydrodynamic force causes friction between the sediment on the surface bed with the flow of water. The increments of water velocity gradually cause sediment in the bed to initiate movement when hydrodynamic forces exceed the threshold values (Armanini 2018).

However, the determination of threshold movement has exhaustively focused on non-cohesive sediments, where the basis of the well-established Shields diagram was developed. Despite the diagram is one of the main references for the incipient motion of sediments, it only shows the characteristics of threshold criteria for non-cohesive sediment. As bed material is a mixture of both non-cohesive and cohesive sediment mixture or could have a significant fraction of cohesive material, it is important to determine the incipient sediment motion on non-homogeneous sediment mixture to a certain accuracy. The determination of threshold criteria is commonly described using the Shields parameter θ_c as

$$\theta_c = \frac{u_{*c}^2}{(s-1)gd}, \tag{1}$$

where u_{*c} is the critical shear velocity. The symbols is $\frac{\rho_s}{\rho}, \rho_s$ is the sediment density, g is the density of water, is the gravitational acceleration and d is the sediment size, often expressed as the median grain size d_{50}.

In recent years many studies have been conducted looking into the incipient sediment motion of cohesive sediment mixture, which comprises of a certain fraction of sand and clay materials. Apart from the cohesive influenced by finer materials of clay or silt, the availability of microorganisms inhabiting the sediments put an influence on the natural character of the sediment. These microorganisms secrete biofilms in the form of a natural polymer called extracellular polymeric substance (EPS) as shown in Figure 1. The EPS increases the sediment stability through physic-chemical interactions between clay minerals and EPS and is promoted by the physical strengthening and glueing by EPS strands (Tolhurst et al. 2002). As such, the transport of cohesive sediment movement is not only influenced by the hydrodynamic and electrochemical forces but also been influenced by the additional strengthening caused by the biological processes.

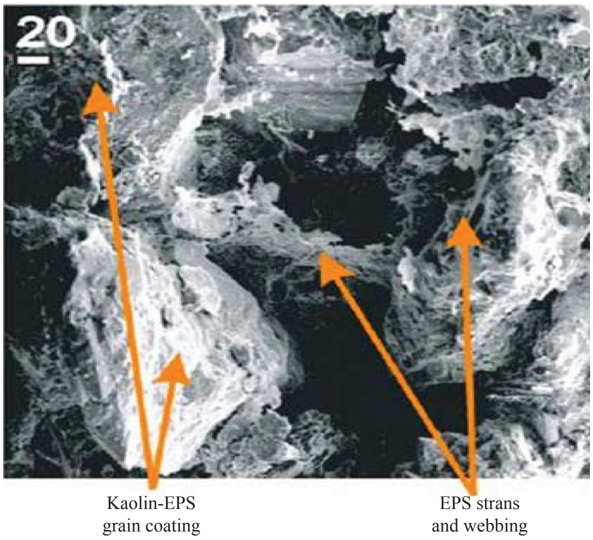

FIGURE 1. Clay (Kaolin) and EPS strands in a high-resolution image of biological cohesive sediment (Parsons et al. 2016)

This study mainly focused on the determination of the incipient sediment motion for biological cohesive sediment in which physical and biological cohesive characteristics comes from the interaction between clay-EPS. EPS produced by microorganisms are complex mixtures of biopolymers consisting of polysaccharides, proteins, nucleic acids, and lipids. EPS form a space between the cells to aggregate and form the structure of microbial biofilms. Thus, the determination of threshold movement of the biological cohesive sediment with high accuracy is necessary to serve as a reference before beginning a construction project, especially in estuaries, coastal and marine delta (Black et al. 2002). The formation of the model dynamic can solve most of the engineering problems such as erosion around bridge piers, the instability of the river cliff, and the determination of erosion in long and short-term period.

METHODOLOGY

The experiment was carried out in a Perspex made flume with dimensions of 0.2 m deep, 0.15 m wide and 4 m long. The study area, which is used to observe the threshold movement, is located at 4.4 m from the upstream with dimensions of $0.6 \times 0.15 \times 0.15$ m^3. The valve and the tailgate located at the inlet and downstream of the flume, respectively as illustrates in Figure 2 controlled the flow velocity (U) and water depth (y).

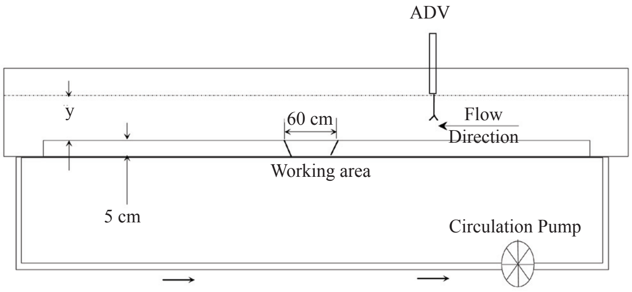

FIGURE 2. The schematic experimental setup

The water velocity profile throughout the experiments was obtained using 3D Acoustic Doppler Velocimetry (ADV) Vectrino Fixes Stem. The equipment was placed on the observation area using a rail as a support and tightened with a screw which can be moved to get the optimum velocity profile. Stem Fixes 3D Vectrino have wires that will be connected to the computer lab and Vectrino Plus software is used which displays experimental parameters needed such as distance from the base, water velocity, and standard deviation.

The sediment layer depth in the working area was set at 5 cm following the false floor located in the upstream and downstream of the working area. The sand-silt-EPS mixture with different percentages of kaolinite (i.e. 10-50%) which has a median grain size d_{50}= 28 μm. Two different concentrations of EPS were tested i.e. at 0.02% representing low concentration whereas 0.1% was used to examine the sediment motion at high concentration of EPS. Fine sand with d_{50}= 150 μm was used in this experiment, which is the dominant material in the sediment mixture.

A series of experiments were done to find the plastic (*PL*) and liquid limits (*LL*) for the cohesive kaolinite-silt material. The result shows that the plastic limit is 23.1 and the liquid limit is 34.9. Plasticity index (*LL*) was equalled to 11.7 which mean that the cohesive material is in the range of slightly plasticity. The procedure for the plastic (*PL*) and liquid limits (*LL*) for the sediment mixture can be referred to Porhemmat et al. (2016) work.

To prepare the sand-silt-EPS mixture, the key aspect is the EPS needs to be homogeneously mixed. A cooking blender with 1% (v/v) water was added and mixed with EPS powder to produce an EPS mixture within the range of plastic limit of 23.1-34.9. The water content was approximately around 25% in the sand-silt-EPS mixture. The homogenously blended EPS and the remaining 24% water content were thoroughly mixed in a modified mechanical mixer to ensure homogeneity in the sand-silt-EPS mixture. Mixtures of sand-silt were prepared with varying percentages of sand/silt as 90/10, 80/20, 60/40, and 50/50 for both different concentrations of EPS. Table 1 shows the percentage of sediment mixture of fine sand, silt, and EPS along with the respective weight of the materials. A total of eight sets of data were conducted in this study.

The sand-silt-EPS mixture was added to the working area in few layers up to 5 cm, whereby during mixture addition for each layer, the mixture was compacted by scraper to ensure a uniform compaction and a flatbed (Porhemmat 2016). The mixture was left to be consolidated in the flume for 18 hours before starting the experiments. This is to enhance the reproduction of organic matter in the mixture with the assistance of EPS.

TABLE 1. Percentage of Sand-Silt-EPS mixture

EPS	Sample	Kaolinite-silt Content		Fine sand content	
0.02% EPS		kg	%	kg	%
equal to	1	3.0	10	27.0	90
6 g	2	6.0	20	24.0	80
	3	12.0	40	18.0	60
	4	15.0	50	15.0	50
0.1% EPS	5	3.0	10	27.0	90
equal to	6	6.0	20	24.0	80
30 g	7	12.0	40	18.0	60
	8	15.0	50	15.0	50

After the consolidation hours have been reached (usually the following day), the water was slowly flowed in by controlling the discharge valve avoid the occurrence of ripple on the flatbed. In the beginning, the valve was slowly opened only to wet the sediment so that the sediment was completely consolidated. A temporary barrier is placed at the end of the experiment to avoid washed sediment from the experimental area and preventing sheet flow conditions. The water level was then gradually increased reaching the height of 15 cm from the sediment surface. A weir gate at the end of the flume was installed to maintain a consistent water level throughout the experiments.

Upon reaching the desired water level, the flow velocity is gradually increased (by systematically increasing the discharge into the flume) until incipient sediment motion was observed. At this point, the mean flow velocity denotes as the critical velocity, U_c measured as the averaged flow velocity. Table 2 shows various definitions of incipient sediment motion by past researches. Note that the table is a representation from the table presented in Beheshti and Ashtiani (2008). In this experiment, the definition of incipient motion was the flow condition at which a few sediment particles on the bed started to move, as suggested by the work of Dey & Debnath (2000). Although many studies commonly adopted the definition number 3 as described by Kramer (1935), we took the criteria set by Dey & Debnath (2000) to account for the non-homogenous sediment mixture used in this study.

The ADV permits the measurement of flow velocities including at horizontal, transversal and vertical directions at 200 Hz frequency. The critical mean velocity allows the calculation of critical shear velocity using the expression

$$u_{*c}^2 = \frac{0.4U_c}{\ln\left(\dfrac{y}{d_{50}}\right)}, \tag{2}$$

TABLE 2. Various definition of incipient motion from few of the researchers

Researcher	Material / Fluid	Definition of the Threshold motion
Kramer (1935)	Sand/ Water	Four different bed shear conditions: (1) no transport – no particles are in motion (2) weak transport – a small number of smallest particles are in motion at isolated zones (3) medium transport – many particles of mean size are in motion (4) general transport – particles of all sizes are in motion at all points and at all times
White (1970)	Sand, crushed silica, lead glass spheres/water	Threshold motion referred to as the condition where a few grains move over a unit area.
Dey and Debnath	Sand/water	The state at which a few sediment particles started to move as the threshold (2000) condition.
Dey and Raju (2002)	Gravel, coal/water	The incipient condition was reached when all fractions of bed particles (on the surface) had movement over a period of time.
USWES (1935)	Sand/water	Set a concept of sediment threshold that tractive force brings about the general motion of bed particles.
Paintal (1971)	Gravel/water	From stochastic points of view that, due to the fluctuating nature of the instantaneous velocity, there is no mean shear stress below the critical value, which can be regarded as zero sediment transport. With this consideration, the critical condition has to be defined as the shear stress that produces a certain minimal amount of transport.

where is the critical shear velocity obtained through experiments. To account for the turbulent fluctuations, the critical root-mean-square (r.m.s.) horizontal flow velocity was also obtained as the standard deviation of the measured horizontal flow velocities. As the mixtures contained different types of materials, the sediment size is described as representative sediment size to consider the state of homogeneity of the (Wu et al. 2004). The representative sediment size is calculated as

$$D = d_{50} e^{-0.5b(\ln\sigma_g)^2}, \tag{3}$$

where d_{50} is sediment diameter size at the 50th percentile (i.e. median grain size), b =1, and σ_g is the gradation parameter. Table 3 shows the representative size of the sediment for all the mixtures.

TABLE 3. Sediment size for different percentage of kaolin

Kaolin (%)	d_{50} (μm)	d_{84} (μm)	d_{16} (μm)	σ_g	D (x 10^{-5})
10	124	208	49	2.06	9.08
20	999	212	17	3.49	3.91
40	553	175	13	3.74	1.95
50	479	168	12	3.78	1.66

The calculation of the critical Shields parameter θ_c was done using both u_{*c} and u_c.

RESULTS AND DISCUSSION

SILT AND EPS EFFECTS ON CRITICAL VELOCITY

Figure 3 demonstrates the effect of silt and EPS percentage on the critical mean velocity . Data shows that by increasing the silt percentage, the critical mean velocity was too increased. The presence of EPS was found to be influential where the higher concentration of 0.1% EPS consistently had higher critical mean velocity than the sand-silt-EPS mixture with a low concentration of EPS of (0.02%).

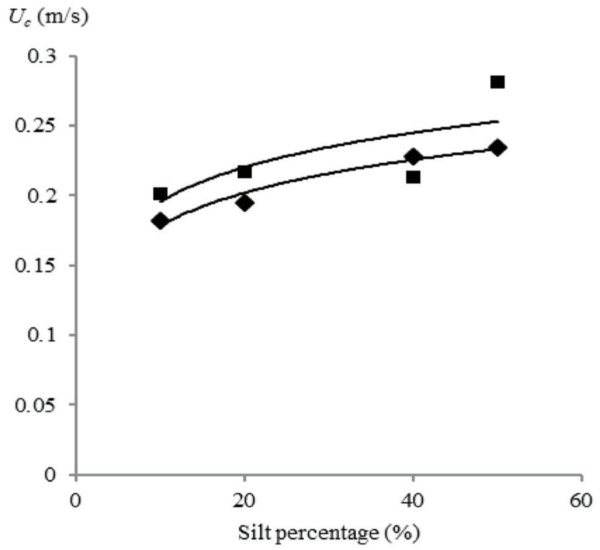

FIGURE 3. The critical average velocity against the percentage of Kaolinite-silt material for 0.1% and 0.02% EPS. The symbols of the square and diamond represent EPS percentage of 0.02 and 0.1, respectivel

SEDIMENT MIXTURE EFFECT ON TURBULENCE

Figure 4 illustrates the turbulence profile along the vertical distance from the bed. The turbulence has fairly consistent value from the upper layer towards the boundary before experiencing a peak value at 1.5 cm from the surface bed. Overflows with varying Reynolds number, the location of peak r.m.s. horizontal velocity is consistently at near bed. From the peak value $\hat{u}_c$, the rms horizontal velocity is then decreasing reaching approximately zero at the bed ($y = 0$) due to the no-slip condition. Thus, in a thin region very close to the bed, it can be said that no (or insignificant) turbulence is presence.

As the turbulence intensity profile is consistent over varying Reynolds number, the presentation of the critical Shields parameter for the turbulent fluctuation (i.e. r.m.s. horizontal flow velocity) is taken as the peak value $\hat{u}_c$.

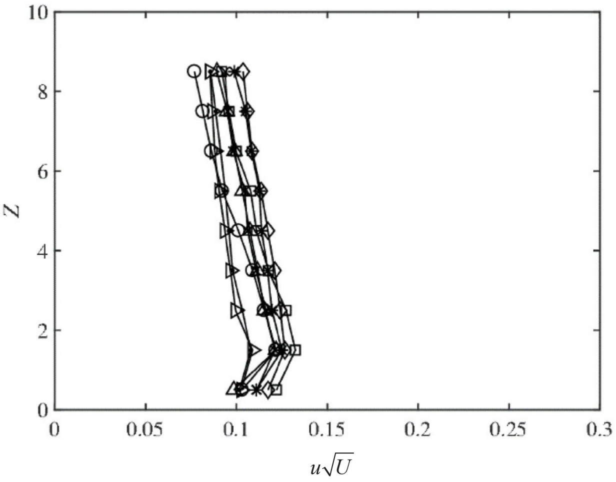

FIGURE 4. The turbulence intensity $u\sqrt{U}$ profile along the vertical distance z from the bed for varying Reynolds number. Each symbol represents associated Re, with Re = 29000 (◦), Re = 31, 000 (□), Re = 36300 (Δ), Re = 36140 (◊), Re = 40000 (*), Re = 46000 (◁), Re = 48000 (•)

INCIPIENT MOTION OF BIOLOGICAL COHESIVE SEDIMENT

The threshold criteria for sediment motion in terms of peak value $\hat{u}_c$, critical mean streamwise velocity U_c, critical shear velocity and associated Shields parameter for sediment mixtures with 0.02% and 0.1% EPS are listed in Table 4. The variation of flow velocities is given to provide a holistic view of the representation of incipient sediment motion.

In general, the presence of EPS increases the threshold criteria of sediment motion throughout the range of Rep discussed in this study. Note that the critical mean velocity (and the r.m.s horizontal flow velocity consistently increased when both the percentages of EPS and kaolinite were increased. Higher kaolinite fractions in the sediment mixture not only reduces the representative sediment size D but also provided more influence for the mixture to behave as cohesive-like sediment.

TABLE 4. Results of critical flow velocities for sediment mixture with 0.02% and 0.1% EPS

KS (%)	Rep	$\hat{u}_c$ (m/s)	U_c (m/s)	U_* (m/s)	θ_c	θ_{c*}
0.02%EPS						
10	3.48	0.023	0.182	0.010	0.363	0.071
20	0.98	0.021	0.195	0.011	0.727	0.179
40	0.35	0.022	0.228	0.012	1.517	0.421
50	0.27	0.025	0.234	0.012	2.313	0.504
0.1% EPS						
10	3.48	0.022	0.201	0.011	0.329	0.088
20	0.98	0.023	0.217	0.012	0.872	0.222
40	0.35	0.023	0.213	0.011	1.626	0.368
50	0.27	0.032	0.281	0.014	3.880	0.728

*θ_c and θ_{c*} are obtained based on the measured and , respectively. KS denotes the percentage of kaolinite-silt mixture.

Although it is expected that with increasing percentage of kaolinite (in the sediment mixture) correlates with the increasing value of threshold criteria, data showed that for 40% of kaolinite, the for 0.1% EPS was slightly lower than the value obtained for 0.02% EPS (Refer Tables 4). This is speculated that as the flow velocity for 20% and 40% percentage of kaolinite sediment mixture was within the similar range (i.e. 0.217 m/s and 0.213 m/s, respectively), errors in visual observation in determining the incipient sediment motion (at 40% kaolinite sediment mixture with 0.1% EPS) is highly likely.

To discuss the pattern of incipient sediment motion, Figure 5 shows the critical Shields parameter θ_c defined using both u_{*c} and $\hat{u}_c$ for different EPS concentration. The data is also compared with the Shields parameter obtained from the similar characteristics sand-silt mixture done by Chuah (2015). The θ_c is plotted against the particle Reynolds number (Re_p), described as

$$Re_p = \frac{D\sqrt{g(s-1)D}}{v}, \tag{4}$$

where v is the kinematic viscosity. The measured θ_c is also described based on the well-established Shields profile using the Brownlie (1982) expression as

$$\theta_c = 0.22Re_p^{-0.6} + (0.06e^{-(17.77\,\mathrm{Re}_p^{-0.6})}) \tag{5}$$

Note that Equation 5 is a representation of the critical Shields parameter based on homogeneous sediment.

It can be seen from Figure 5(a) that incipient sediment motion for sand-silt-EPS with 0.02% EPS has insignificant changes than the ones obtained for sand-silt mixture over the range of Re_p discussed in this study. This indicates that sediment low EPS concentration do not have a significant effect on the threshold motion of sediment. The description of θ_c is higher of the orders (1) when calculated using critical rms horizontal velocity than when described using critical shear velocity.

On contrary, data from Figure 5(b) shows higher threshold criteria for sand-silt mixture with higher concentration EPS i.e. 0.1%. The θ_c values are consistently above the values obtained from the sand-silt mixture in Chuah (2015). The additional strength from EPS and consolidation hours obviously increased the cohesiveness of the sediment mixture. Higher flow velocity and turbulence are needed to break the bonding between particles and initiate movement. The critical Shields parameters were evidently varied when presented using a different scale of velocities. The values of θ_c using critical shear velocity is lower than θ_c calculated based on the critical r.m.s horizontal flow velocity.

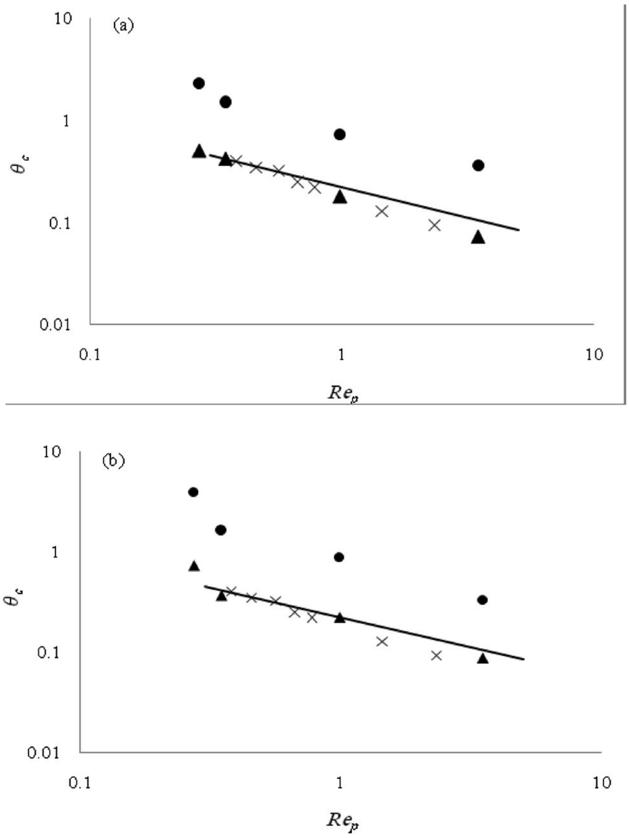

FIGURE 5. Critical Shields parameter against particle Reynolds number for mixtures that contain EPS of (a) 0.02% and (b) 0.1%. The symbols of triangle and circle represent θ_c calculated using u_{*c} and $\hat{u}_c$, respectively. The solid line is the well-developed Shields curve

Parsons et al. (2016) studied the formation of bedform steepness for varying percentages of EPS in a sand-silt sediment mixture. Similar flow characteristics was observed in bedform steepness for a mixture with 0.3% EPS and a consolidated sand-silt mixture. Higher concentration of EPS increased the cohesiveness of the mixture where the bed was found flat and no bedform was observed, even at the same flow velocity. Even the addition of EPS is only 1% in a sand-silt sediment mixture, the higher flow velocity is needed to initiate sediment movement.

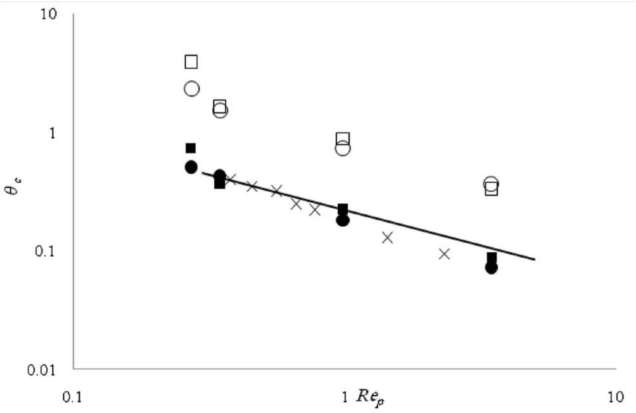

FIGURE 6. The comparison of critical Shields parameter θ_c for the sand-silt-EPS mixture using the variation of representation in critical velocities. The θ_c obtained based on shear velocity u_{*c} and $\hat{u}_c$ r.m.s horizontal velocity $\hat{u}_c$ are represented by the circle and square symbols, respectively. The unfilled in symbols denote observed data for 0.02% EPS whereas the filled symbols are the values obtained based on 0.1% EPS experiments. The solid line is the Shields curve

Based on the observed trend for profile of sand-silt-EPS mixture (when calculated using and the Shields curve developed based on non-cohesive sediment, it can be said that the percentage of silt and EPS do not consequential influence on the incipient sediment motion.

To provide an overview comparison between the effects of EPS concentration, silt percentage on incipient sediment motion of a sediment mixture, a plot with all data as shown in Figure 6 was done. Data shows that the critical Shields parameter based on the r.m.s. horizontal flow velocity $\hat{u}_c$ is consistently higher than when the presentation based on u_{*c}. This is believed due to the value of $\hat{u}_c$ represents the turbulent fluctuations at near bed whereas the critical shear velocity is a pseudo scale velocity representing shear stress at the boundary layer.

CONCLUSION

This study investigated the effect of biological influence on the cohesive-like incipient sediment motion based on the traditional critical shear velocity and turbulent fluctuations in the form of root-mean-square horizontal flow velocity. A controlled percentage of EPS is added into the sediment mixture to imitate the biopolymer layer produced by microorganisms and indicate the presence of biofilm with the grain particles. The influence of EPS is not significant on the threshold criteria at low concentration of 0.02% but the strengthening of the mixture became evident at a higher concentration of EPS, which increased the critical Shields parameter values.

Despite different interpretation of θ_c based on the varying scale of velocity, the similar trend of Shields profile to the well-established curve was obtained. Higher θ_c was observed as the particle Reynolds number become smaller.

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Najwa Izzaty Muhammad Azha
*Wan Hanna Melini Wan Mohtar
Civil Engineering Programme
Smart and Sustainable Township Research Center,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, Bangi, Malaysia.

*Corresponding author; email: hanna@ukm.edu.my

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