Threshold Criteria of Sediment Motion for Biological Cohesive Sediment Mixture

(Kriteria Pergerakan Ambang Sedimen bagi Campuran Sedimen Jelekit Biologi)

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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 rajah 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 pemantauan. 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. Keadaan 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 memeriksa pergerakan ambang sedimen adalah faktor tidak penting.

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 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. Fluval 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 \( \theta_c \) as

\[
\theta_c = \frac{u^2_c}{(s - 1)gd},
\]

where \( u_c \) is the critical shear velocity. The symbols is \( \frac{\rho_s}{\rho} \), \( g \) is the density of water, \( g \) 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 physicochemical 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.

![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 (\( y \)).
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**

<table>
<thead>
<tr>
<th>EPS Content</th>
<th>EPS Sample</th>
<th>Kaolinite-silt Content</th>
<th>Fine sand content</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02% EPS</td>
<td>1</td>
<td>3.0</td>
<td>10</td>
</tr>
<tr>
<td>equal to 6 g</td>
<td>2</td>
<td>6.0</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>12.0</td>
<td>40</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>50</td>
<td>15.0</td>
</tr>
<tr>
<td>0.1% EPS</td>
<td>5</td>
<td>3.0</td>
<td>10</td>
</tr>
<tr>
<td>equal to 30 g</td>
<td>6</td>
<td>6.0</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>12.0</td>
<td>40</td>
<td>18.0</td>
</tr>
<tr>
<td>1</td>
<td>3.0</td>
<td>10</td>
<td>27.0</td>
</tr>
<tr>
<td>equal to 0.1% EPS</td>
<td>5</td>
<td>3.0</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>6.0</td>
<td>20</td>
<td>24.0</td>
</tr>
<tr>
<td>8</td>
<td>15.0</td>
<td>50</td>
<td>15.0</td>
</tr>
</tbody>
</table>

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 & Deb Nath (2000). Although many studies commonly adopted the definition number 3 as described by Kramer (1935), we took the criteria set by Dey & Deb Nath (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

\[
\frac{U_c^2}{
u} = \frac{0.4U_c}{\ln \left( \frac{y}{d_{90}} \right)},
\]

where

- \( U_c \) is the critical mean velocity
- \( \nu \) is the kinematic viscosity
- \( y \) is the elevation
- \( d_{90} \) is the diameter of the 90th percentile.
TABLE 2. Various definition of incipient motion from few of the researchers

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Material / Fluid</th>
<th>Definition of the Threshold motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kramer (1935)</td>
<td>Sand/ Water</td>
<td>Four different bed shear conditions:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1) no transport – no particles are in motion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) weak transport – a small number of smallest particles are in motion at isolated zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) medium transport – many particles of mean size are in motion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) general transport – particles of all sizes are in motion at all points and at all times</td>
</tr>
<tr>
<td>White (1970)</td>
<td>Sand, crushed silica, lead glass spheres/water</td>
<td>Threshold motion referred to as the condition where a few grains move over a unit area.</td>
</tr>
<tr>
<td>Dey and Debnath (2000)</td>
<td>Sand/water</td>
<td>The state at which a few sediment particles started to move as the threshold (2000) condition.</td>
</tr>
<tr>
<td>Dey and Raju (2002)</td>
<td>Gravel, coal/water</td>
<td>The incipient condition was reached when all fractions of bed particles (on the surface) had movement over a period of time.</td>
</tr>
<tr>
<td>USWES (1935)</td>
<td>Sand/water</td>
<td>Set a concept of sediment threshold that tractive force brings about the general motion of bed particles.</td>
</tr>
<tr>
<td>Paintal (1971)</td>
<td>Gravel/water</td>
<td>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.</td>
</tr>
</tbody>
</table>

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

$$D = d_{50} e^{-0.5/b \sigma_g} \sqrt[50]{d_{50}}.$$  

(3)

where $d_{50}$ is sediment diameter size at the 50th percentile (i.e. median grain size), $b = 1$, and $\sigma_g$ is the gradation parameter.

Table 3 shows the representative size of the sediment for all the mixtures.

<table>
<thead>
<tr>
<th>Kaolinite (%)</th>
<th>$d_{50}$ ($\mu$m)</th>
<th>$d_{16}$ ($\mu$m)</th>
<th>$d_{84}$ ($\mu$m)</th>
<th>$\sigma_g$</th>
<th>$D$ ($\times 10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>124</td>
<td>49</td>
<td>208</td>
<td>2.06</td>
<td>9.08</td>
</tr>
<tr>
<td>20</td>
<td>999</td>
<td>17</td>
<td>212</td>
<td>3.49</td>
<td>3.91</td>
</tr>
<tr>
<td>40</td>
<td>553</td>
<td>13</td>
<td>175</td>
<td>3.74</td>
<td>1.95</td>
</tr>
<tr>
<td>50</td>
<td>479</td>
<td>12</td>
<td>168</td>
<td>3.78</td>
<td>1.66</td>
</tr>
</tbody>
</table>

The calculation of the critical Shields parameter $\theta$ was done using both $u_c$ and $u_*$. 

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](chart.png)
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 $\bar{u}$, 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 present.

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 $\bar{u}$.

![Figure 4: The turbulence intensity $u\sqrt{\bar{u}}$ 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 (□), Re = 36140 (△), Re = 40000 (•), Re = 46000 (◦), Re = 48000 (✦)](image)

**INCIPENT MOTION OF BIOLOGICAL COHESIVE SEDIMENT**

The threshold criteria for sediment motion in terms of peak value $\bar{u}$, critical mean streamwise velocity $U_*$, 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 $Re$ 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](image)

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 $\theta_*$ defined using both $\bar{u}$ and $\bar{u}$ 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 $\theta_*$ is plotted against the particle Reynolds number ($Re_p$), described as

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

(4)

where $\nu$ is the kinematic viscosity. The measured $\theta_*$ is also described based on the well-established Shields profile using the Brownlie (1982) expression as

$$\theta_* = 0.22Re_p^{0.6} + (0.06e^{(-17.77Re_p^{0.6})})$$

(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 $Re$ 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 $\theta_*$ 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 $\theta_c$ 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 $\theta$ using critical shear velocity is lower than $\theta_c$ calculated based on the critical r.m.s horizontal flow velocity.

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 $\bar{u}$ is consistently higher than when the presentation based on $u^*$. This is believed due to the value of $\bar{u}$ 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 $\theta$ based on the varying scale of velocity, the similar trend of Shields profile to the well-established curve was obtained. Higher $\theta_c$ was observed as the particle Reynolds number become smaller.
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